Agricultural land use planning: exploring the potential of spatial agent-based modelling (ABM)

by

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Declaration of Originality

This thesis contains no material which has been accepted for a degree or diploma by the University or any other institution, except by way of background information and duly acknowledged in the thesis, and to the best of my knowledge and belief no material previously published or written by another person except where due acknowledgement is made in the text of the thesis, nor does the thesis contain any material that infringes copyright.

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Abstract

This thesis advances capability in agricultural land use planning by considering how human-natural system interactions influence agricultural land use patterns. The research has developed an approach to simulation of different agricultural scenarios through integrating spatial agent-based modelling (ABM) with geographic information systems (GIS). This approach enables the biophysical and the human factors that influence regional development to be integrated into models that can generate a range of future scenarios for planning purposes. The outputs of this research will enable farmers, land use planners and policymakers such as local government to use it as a tool to gain insights into potential agricultural land use changes and new options for irrigated land to assist them in their decision-making.

The complexity of land use planning – specifically agricultural land use planning in Australia – raises considerations about what methods and planning support tools might effectively aid decision-making on land and water resources. Too often land use decisions made by farmers and the cumulative impact of those decisions are not reflected in land use planning, nor is their response to change and innovation. This thesis addresses these drawbacks by developing a simulation model designed to explore agricultural land use scenarios through a bottom-up planning approach.

The pragmatic nature of this research required an advanced mixed method design to enable qualitative and quantitative data collection and analysis across a multistage process. This study had three stages similar to the Geodesign methodology (notably agent-based design), implemented in its adaptation via Agent Analyst software, the outcome of which was the Crop GIS-ABM.

In stage one, a cross section of stakeholders (farmers, planners, local government and State irrigation bodies) were interviewed and surveyed to identify key factors that influence

farmers' land use decisions. These qualitative and quantitative data were merged to frame a conceptual model of farmer decision-making. In stage two, the workflow for the integration of stakeholders' insights and knowledge with spatial ABM was mapped and the influential decision factors were synthesised into algorithms, and the Crop GIS-ABM was developed. In the third stage, the model was run to simulate a set of agricultural scenarios and explore how farmers make decisions under changing conditions such as introduction of a new irrigation scheme or new alternative crops.

The Dorset region in Northern Tasmania was selected as a case study to 'test' the simulation model for largely pragmatic reasons of proximity, local relevance, available GIS data as well as experiencing change transitioning from traditional crops to higher value-added production as access to guaranteed water expands.

This research demonstrates the potential effectiveness of a spatial ABM as a decision support simulation tool for agricultural land use planning. The Crop GIS-ABM makes an important contribution to the literature on spatial ABM simulation because it includes stakeholders' insights and integrates both qualitative and quantitative data into spatial ABM. The primary contribution of this research is to enable planning to better capture the cumulative impact of many individual decisions by farmers on land use change. Further research using a similar design methodology could explore the factors driving farmers' decision-making in other regions of Australia and the world. However, this present research takes urban and regional planning a little closer to a better understanding of how dynamic individual farmer decisions influence the emergence of regional land use patterns and the value of simulation as a planning tool.

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Many heartfelt thanks to you all for helping me to achieve my goals.

Dedication

This thesis is dedicated to **Mehrdad** who encouraged me to pursue my dreams and finish my PhD.

Photo by Mehrdad Abbasian

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Chapter 1: Introduction and thesis structure

1.1 Introduction

Land and water resources are important to sustainability of agricultural production. Challenges such as climate change, urban encroachment and land degradation drive changes in the agricultural landscape. Technological innovations, local and global economies and land use policy influence farmers' decisions. Farmers' activities and decisions transform agricultural land use. However, cumulatively the individual decisions by agricultural stakeholders, shape land use and water utilisation and have direct and indirect regional consequences over time. Cumulative regional impacts of individual farmer decisions are not well reflected in land use planning, nor their response to change and innovation. Therefore, there is a need to address these concerns and the complexity of agricultural land use planning.

Agricultural land use is influenced by, not only multiple aspects of biophysical and socio-economic processes, but also the cumulative impacts of individual farmer decisions. In this framework, planning for agricultural land use is a complex process, possibly even more so than urban land use planning and is not specific to any geographic context and region. This complexity is due, in part, to the nexus of water use, land use and agricultural policies combined with the dynamic decision-making surrounding farming activities. Tackling the complexity of agricultural land use planning requires a model-based approach and tools that account for the multiple biophysical, social, economic and political drivers that are common across agricultural-based production regions.

This study explores the potential for simulation model for agricultural land use planning. This research proposes a modelling approach to facilitate agricultural land use planning with a focus on responding to change and innovation (i.e. to optimise future individual and regional benefits of irrigation investment). The research was undertaken in the context of Tasmania. Dorset region in NE Tasmania was selected as a case study, for largely pragmatic reasons of high local relevance, available GIS data as well as being a bounded geographically defined area experiencing change. Dorset is a region undergoing irrigation expansion transitioning from traditional crops to higher value-added production as access to guaranteed water from irrigation becomes available. The potential application of irrigation is for increasing production of both traditional and alternative crops with choices affected by changing commodity prices. Dorset therefore encompasses many of the land use planning pressures faced by agricultural regions in other parts Tasmania as well as other States in Australia. The Dorset region was therefore an appropriate region to 'test' the simulation model and explore outcomes of various scenarios.

Projecting regional benefits from the outcome of change and innovation, in this case new irrigation systems, is a fundamental step in developing the economic and social licence to proceed with the investment. It is a process that requires consideration of the opportunities that can be generated from dedicating water and land resources into new irrigation schemes to support intensified existing production systems and to yield new value-add opportunities.

The focus of this study was to develop a decision support simulation model to tackle the complexity of the decision-making process in these kinds of contexts by simulating how human-natural systems interact under different agricultural scenarios. Specifically, this research examines the ability of a spatial agent-based modelling (ABM) to understand how farmers' dynamic behaviours influence the emergence of agricultural land use patterns. Macro-scale (regional) and micro-scale (farm) scenarios can be simulated using the spatial ABM to examine options for optimising the benefits of regional agricultural land use through irrigation expansion.

The following sections describe the research context, the aim and significance, the problem statements, research questions and methodology of the research.

1.2 Research context

Australia's land area is around 7.7 million square kilometres, and in 2017 the population, which has doubled since 1970, was almost 24.7 million. In 2016-17, around 51% of Australia's land area was used for agricultural purposes (Australian Bureau of Statistics 2018), and agricultural water extraction was around two-thirds (70%) of the total Australian water use (Australian Government Bureau of Meteorology 2017).

Historically, agricultural and forest products, as well as minerals commodities, have been the basis of Australia's economy (Thackway 2018). The trade-off between Australia's natural resources (e.g. land and water) and human interests and modifications are the drivers of land use change in Australia. Policy and planning by Federal, State and Local governments also have significant impacts on the spatial and temporal pattern of land use change. The classification of landscape attributes, surveys of current land management regimes and mapping of ecological conditions help decision-makers to gain insights into natural resource conditions of land and water (Thackway & Lesslie 2008).

Tasmania is an island State of Australia that is in the process of developing extensive new irrigation systems. Tasmania's economic strengths lie in natural resources including its fertile soil types and water for agricultural land use expansion. Tasmania is also expected to experience less severe climate change impacts compared to other parts of Australia due to its temperate maritime climate (Hennessy et al. 2008). Agriculture plays a vital role in the State's economy (the second-largest sector of the Tasmanian economy in 2016-2017), and the most important commodities of agricultural production (50% of the total value of agricultural production) were milk, cattle and potatoes (Eslake 2017; Department of Agriculture & Water Resources 2018). There is a positive future for agriculture in Tasmania (West 2009). However, there are challenges, such as the growing competitiveness of national and global markets for agricultural products, and climate change (Tasmanian Government 2017). In relation to climate change, although the severity may not be as high as the rest of Australia, there is the possibility of an increase in exceptionally hot and dry years (Antarctic Climate and Ecosystems Cooperative Research Centre 2010; Climate Council 2016).

Tasmania holds around 12% of Australia's freshwater resources (Australian Bureau of Meteorology 2012) but less than 2% of the nation's population (Australian Bureau of Statistics 2017). Therefore, Tasmania's approach to land and water use is of necessity different from the rest of Australia as evidenced in various plans and schemes (Skills Tasmania 2011; Tasmanian Climate Change Office 2012; Regional Development Australia Tasmania Committee (RDA) 2015). While Tasmania generally experiences reliable rainfall in winter and spring, recent evidence suggests that climate change will reduce rainfall in summer and autumn with detrimental effects on Tasmania's pasture productivity (Phelan et al. 2015; Harrison, Cullen & Rawnsley 2016). Declining rainfall in catchment areas may limit the potential to store runoff water that could otherwise be used for irrigation. Thus, water availability and security are critical to agriculture development in the long term. There is potential for agriculture to grow in all arable regions with the development of new irrigation schemes (Skills Tasmania 2011). Therefore, it is important to make more informed decisions on a regional scale to better manage agricultural land and water resources in Tasmania.

1.3 Problem Statement

In spite of the importance of the agriculture sector to Tasmania's economy (Department of Agriculture & Water Resources 2018) and the significance of irrigation for the productivity of agricultural products, the scenario outlined above highlights the need to improve decision-making processes around the future of agricultural land and land use change when interventions such as irrigation and associated technologies are introduced. There is a need for a planning tool for better capturing multiple aspects of biophysical and socio-economic processes as well as the cumulative impacts of many individual farmer decisions on agricultural land use change. Stakeholder decisions and choices, especially those of farmers, are not well or easily incorporated in traditional land use planning approaches and tools. The challenge is to access a planning tool that can account for the multiple factors that affect land use planning and decisions.

The Department of Primary Industries and Water in Tasmania (2008) developed the 'Tasmanian irrigation development projects: Drought Proofing Tasmania Strategy', which aims to provide water security for rural communities, allowing growth in irrigated land and improving agricultural production. This points to an opportunity not only to better manage and distribute the water resources in Tasmania but also to identify the potential to extract the best value from each litre of water conserved and used for irrigation under the drought proofing strategy (Productivity Commission 2009). It also has significant implications for the treatment of agricultural land in land use planning schemes. The introduction or expansion of water resources, for example, allows new kinds of farming activities to be introduced and new crops to be considered especially if they generate higher returns. These are decisions that not only affect individual livelihoods but also have regional or macro-scale implications.

Optimising the regional benefits from implementing new irrigation water supplies is a complex process that involves consideration of opportunities generated from available water and land areas. Certainly, for regional and agricultural land use planning, it is necessary to consider irrigation expansion in the context of agricultural water demands under future uncertain climatic conditions. But on the other hand, integrating stakeholder knowledge in land use planning is also an important component of future land development. It is crucial to know who the stakeholders are to capture what their points of views are around agricultural land use development.

Tasmanian farmers are concerned about the long term sustainability of their agricultural production under climate variability (Harrison, Cullen & Rawnsley 2016; Tasmanian Institute of Agriculture n.d.). The need to optimise benefits from fertile soils, reliable rainfall and sunshine sits at the centre of considerations about the future of Tasmanian agriculture (Dairy Tas 2018). Intensification and extensification of agricultural zones are critical decisions. Intensive agricultural development, for example, can lead to potential problems and challenges such as land degradation and soil erosion that threatens the sustainability of land use. Further, decisions for Tasmanian agriculture need to focus on how farmers can best utilise water and land to produce higher-value returns to cover investment costs.

Tasmanian Irrigation was set up as a State company in 2008 to improve the capacity and productivity of Tasmanian agriculture by developing irrigation schemes and delivering water to farmers (Tasmanian Irrigation (TI) n.d.). Tasmanian Irrigation's role is to improve the efficiency of water resources for sustainable agricultural production by developing irrigation schemes that attract farmer investment and enable water trading. However, this is a complex decision process. The expansion of irrigation in the region can affect multiple stakeholders and the community. There is therefore a need to find ways to account for stakeholder concerns and expectations, and to gain social acceptance from the local community.

The Tasmanian Planning Commission was established as an independent body to assess planning schemes and provide advice in respect of matters related to State and regional strategic land use planning (Tasmanian Planning Commission n.d.). The Commission performs a range of statutory and advisory functions for local governments in Tasmania in relation to planning schemes under the Land Use Planning and Approvals Act 1993. The planning challenge in the context of agricultural land and water resources is how to balance agricultural development and environmental conservation and sustain both agricultural production and natural resources in Tasmania. This is all the more critical given the importance of both the agricultural sector and the the social and tourism value of the natural landscape to Tasmania's economy.

The challenge is that decision-making about agricultural land use and the implementation of change, such as new irrigation schemes at the regional scale, are complex and must involve consideration of different stakeholders such as farmers, local government, State bodies and others along the agricultural value chain such as the food processing industry and the broader community. In the example of irrigation, which is a significant land use intervention, considering the perspectives and interests of different stakeholders increases both the legitimacy and the social licence of irrigation scheme implementation. However, it adds some levels of complexity with higher numbers of participants. A further issue is how the different spheres of government, the community and industry can collaborate for shared responsibility of agricultural land use sustainability.

Most of the existing decision support systems on land use and water management have focused on biophysical and landscape change (Seabrook, McAlpine & Fensham 2006). For example, the Multi-Criteria Analysis Shell for Spatial Decision Support (MCAS-S) concentrates mostly on sustainable management of landscapes (Hill et al. 2005; Thackway 2018), but socio-economic data and human decisions and activities were not linked to the model. However, the complexity of decision-making on agricultural land use points to the need for decision support systems that do account for the economic, social and environmental factors as well as different stakeholders' decision factors and the dynamics of interactions between the human-natural system.

1.4 Aim and purpose

The overall aim of this thesis is to assist farmers, land use planners and policymakers (i.e. local government) to gain insights into land use change through simulation of different agricultural scenarios involving irrigated land and water use options. This research provides insights into agricultural land use planning by developing a spatial ABM and integrating economic, environmental and social factors contributing to the expansion of irrigated land use areas as an example of change in agricultural land use. The research demonstrates how the integration of stakeholders' insights within a modelling approach can provide a better understanding of how dynamic human behaviours influence the emergence of regional land use patterns.

The purpose of this study is to answer research questions and develop a methodology that assists farmers, land-use planners and policymakers (i.e. local government) to gain insights into land-use change through simulation of different agricultural scenarios involving irrigated land and water use options. This research explores the use of simulation modelling to envisage the potential effects of land use change and the cumulative impacts of farmers' decisions – in this case the potential impacts of newly available irrigation on agricultural land use change. The intended application is not for predictive or forecasting purposes, but to gain greater understanding about the potential impacts in order to influence planning decisions.

1.5 Research questions

This study uses interdisciplinary approaches to land use planning to address the complexity of agricultural land use changes. The aim of this thesis is to provide a better understanding of how dynamic human behaviours influence the emergence of agricultural land use patterns. The overarching theme and primary research question of this study was formulated as follows:

- *Could agricultural land use planning in Australia benefit from a decision support simulation model, and in what ways could a simulation model be useful?*

To address and answer the central question a series of sub-questions were asked to facilitate the research design, data collection, and exploring of a spectrum of possible scenarios arising from using a decision support simulation model. The research sub-questions were:

- *Q1- What economic, social and environmental factors influence farmers' decisions on crop choice and what are their relative impacts?*
- *Q2- What kind of simulation model is required for the integration of qualitative and quantitative data with ABM in a GIS-based 'virtual laboratory'?*
- *Q3- Could farmers' decisions and behaviours on adoption of new alternative crops be simulated to answer: To what extent does the irrigation expansion promote the diffusion of alternative crops in the region? How does farmers' crop choice alter the regional land use and the crop patterns over time?*

The research questions are sequential and addressing them involves several stages. This has influenced the methodology which, as Chapter 3 will show, has been informed by the geodesign methodology developed by Steinitz (2012). The research requires both qualitative and quantitative data and this too has shaped the methodology.

1.6 Research Methodology

The overall approach of this research was pragmatic and mixed-method research methodology was employed for data collection and data analysis. Multistage mixed-method design, as described by Creswell (2015), was adopted to design a structured process for integration of the methods and techniques. The multistage design of this study was aligned with geodesign methodology (Steinitz 2012). Figure 1-1 shows the overview of research structure. Chapter Three explains the research methodology and the multistage mixed method research in detail.

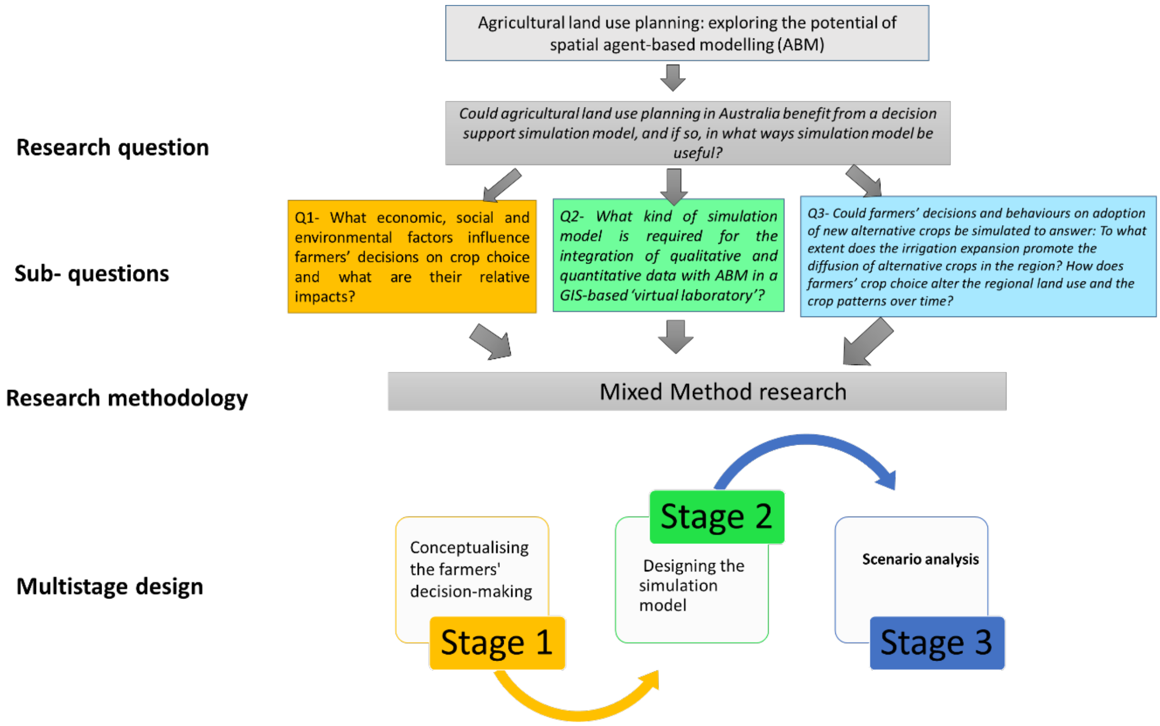


Figure 1-1 Overview of research structure

1.7 Thesis structure

As Figure 1-2 illustrates, the thesis is organised into seven chapters as follows.

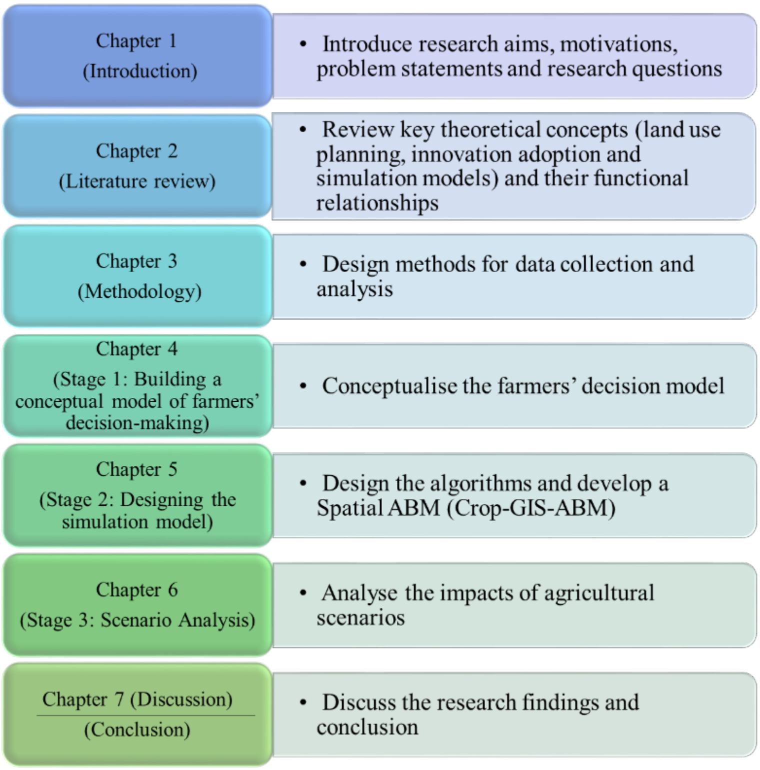


Figure 1-2 Thesis structure

Chapter One introduces the research and presents the research motivations in relation to simulation modelling within the context of Australian agricultural land use planning, the aim, and the significance of the research. This Chapter also describes the statements of research problems and research questions, and the research approach to answer the questions. The research scope, the benefits of the research and thesis structure are presented.

Chapter Two focuses on reviewing the literature on the subject of agricultural land use planning in the context of previous studies. This Chapter starts with the introduction to the concept of land use, and water use and land use planning in Australia, discussing different factors that influence agricultural land use planning. The Chapter reviews the adoption of innovation in the context of agricultural change and also covers the topics of simulation models, benefits and limitations.

Chapter Three describes the methodology and research design employed for this research. This Chapter discusses data collection methods, sampling techniques and data analysis methods. Chapter Three also discusses the procedure for the integration of qualitative and quantitative data into the simulation model, methods and techniques.

Chapter Four focuses on developing a conceptual model, building a simulation model and testing the model. This Chapter describes the scope of the case study and the stakeholders' insights on land and water use in the study area and discusses the factors that influence stakeholders' decisions on crops/livestock choices, for the purpose developing a conceptual model.

Chapter Five explains how the conceptual model was built on an ArcGIS platform and via Agent Analyst software. This Chapter illustrates the process of developing the algorithms and the design process of the Crop GIS-ABM simulation model.

Chapter Six presents the capability of Crop GIS-ABM model to simulate farmers' behaviour and interactions in a GIS-based 'virtual laboratory'. This Chapter focuses on different agricultural scenarios and investigates how farmers' decisions on adoption of new alternative crops/livestock and irrigation expansion alter the land use patterns. Chapter Six presents general discussions on the outcomes of simulations under different experimental conditions.

Chapter Seven discusses the research findings by providing a summary and themes drawn from the study and answering the research questions. This Chapter highlights the contribution of this study to the body of knowledge and provides some recommendations for future research.

1.8 Study rationale and significance

The motivation for undertaking this research was to develop a simulation tool for agricultural land use planning, to bridge the gap between land use planning and land use science. This research aims to assist agricultural land use planning by exploring how the human-natural system might interact. This is done through simulation and scenario analysis as a means to gaining a better understanding of how farmers' choices can alter the regional land use pattern. To do this, important factors that influence farmers' decisions on irrigation expansion and agricultural enterprise were identified. A decision support simulation tool was then built based on integrating these influential factors with geographic information systems (GIS) to enable the examination of several agricultural scenarios for exploring agricultural land use change under irrigation expansion. The broader argument is that decision-makers can use this kind of spatially based simulation tool to explore possible future effects of their decisions on agricultural land before deciding on irrigation expansion.

Land use science is an interdisciplinary science that attracts researchers from a range of disciplines, including economics, sociology, geography, geographic information systems (GIS) and remote sensing and demography (Zscheischler & Rogga 2015; Zvoleff et al. 2017). For this research a particular driving factor was the scientific literature and official reports and documents that had recognised the important role of regional land use planning and policy in delivering and protecting sustainable use of land and water resources (Tasmanian Irrigation 2012; Cottee-Jones 2013; Regional Development Australia Tasmania Committee (RDA) 2015; Tasmanian Planning Commission n.d.).

The nexus between land use science (especially geography oriented sciences and spatial data) and policy is complex and insufficient (Dovers 2018). A better understanding of the integration of scientific and political processes has been identified as a critical driver of sustainable land use and water use (Head 2008; Dovers & Hussey 2013). Effective spatial decision support systems, and the improvement of visual representation and mapping tools have been identified as steps towards more effective collaboration among stakeholders to enable them to make more informed decisions on land use planning (Baral, McDougall & Chong 2011; Steinitz 2012; Lesslie & Mewett 2013).

This study was therefore conducted to develop a spatial simulation model for the purpose of land use planning and sustainable agricultural development. The investigation explored potentials of a spatial ABM to assist decision-makers at the macro-scale (policymakers) and micro-scale (farmers) to tackle the complexity of decision-making processes on agricultural land use and water use. Specifically, the study was designed to investigate (1) stakeholders' decision processes and (2) human-natural resource interactions, and to develop a decision support simulation tool that enables spatial visualisation and better communication with different stakeholders. The significance of this research is four-fold.

First, as stated earlier, land use planning in Australia is a complex process and may involve conflicts of interest in land and water management among different stakeholders. Indeed, there have often been disagreements over the best use of land and water resources (Mercer 2000; Schirmer 2018). One of the planning issues in Australia is the pressure and demands for agricultural land use to be converted to urban and peri-urban land use (Thackway 2018). This research presents an example of investigating different perspectives on land use and water use by involving various stakeholders' insights into the modelling process to overcome the challenges of the legitimacy of decision-making.

Second, agricultural land use policy affects communities differently at local, regional, State and national levels depending on environmental, economic and social factors (Lubowski et al. 2006; Gutzler et al. 2015). It is essential that land use planners have access to the latest scientific modelling and scenario tools to test the different social, economic and environmental outcomes and the possible impacts of their decisions (Thackway 2018). This study aims to aid decision-making on land and water use by developing a simulation model to test different agricultural scenarios in the context of expanded irrigation coverage in the State of Tasmania. The model provides decision-makers and other stakeholders with a conceptual foundation to gain insights into agricultural land use change under irrigation expansion on the regional scale.

Third, this research investigates how spatial, economic and agronomic considerations, as well as human judgments and dynamic decisions, can be integrated through simulation modelling. This research shows how qualitative data and quantitative data were combined to build a simulation model. It also demonstrates how a bottom-up modelling approach in the context of land use planning affords the potential to explore different agricultural scenarios digitally and capture the influence of micro-scale decisions on the emergence of macro-scale patterns.

Finally, this research contributes to studies on spatial ABM simulation in the context of agricultural land use planning and decision-making. The specific contribution of this research is the integration of stakeholders' insights with an ABM approach in the GIS platform – the Crop GIS-ABM – resulting in an approach for understanding the dynamic decision-making process on agricultural land and water. The research proposes that not only can the complexity of the human decision-making process be captured through spatial ABM, but also that human behaviour and interaction with their region can be explored through simulation. This research proposes that spatial ABM is a promising computational model for simulating agricultural land use patterns under different experimental conditions such as new alternative crops/livestock, irrigation expansion and milk price.

1.9 Research Scope

The scope of this study was limited to the context of Australian agricultural land use and water use modelling and planning and more particularly Tasmania where the issues relating to water are as much about change and innovation as about drought proofing. Although the methodology could be applied to other related contexts, the research was based on agricultural land use change under irrigation expansion in the Dorset region, in the North East of Tasmania. The Dorset region was selected because it has been going through a change from traditional crops to higher value-added production with access to guaranteed water, and there are significant opportunities for the region to consider new alternative crops/livestock and value-added processing. As will be discussed further in Chapter 3, the spatial data was based on GIS layers and maps from DPIPWE, Tasmanian Irrigation (TI), and the Land Information System Tasmania (LIST) website. Stakeholders in the Dorset region generously agreed to be interviewed to investigate their experience and insights on the influential factors that drive land and water use decisions. Author of this research cannot be responsible for the truth of the information provided by respondents if proper due diligence has been followed.

1.10 Benefits of research finding

This study has potential benefits for the Australian agricultural industry, and the Australian planning systems and their stakeholders such as farmers, planners, local government, State irrigation bodies and the food processing industry. The benefits include:

- Development of a process for integrating stakeholders' experience, knowledge and insights with spatial ABM
- Integration of social, environmental and economic data (both quantitative and qualitative) in a spatial ABM
- Integration of socioeconomic and biophysical data with spatial data
- An appropriate and realistic geographical visualisation of simulation outcomes for better exploration of the effects of agricultural scenarios
- Helping decision-makers to gain insights into natural resource conditions of land and water use and to explore the possible outcomes of agricultural scenarios

- Broader applications of the model for urban and regional planning, agricultural land use planning, crop yield, irrigation policy, and agricultural innovation adoption.

The Crop GIS-ABM that was developed in this study can facilitate agricultural land use planning to optimise the future regional benefits of irrigation. It also can assist decision- makers in exploring plausible spatial and temporal changes that might emerge in land use as a result of their irrigation expansion policy and plans.

Chapter 2: Developing a theoretical platform - identification and review of key concepts

2.1 Introduction

This Chapter outlines the key research themes and concepts associated with agricultural land use to underpin the research aim and the key research questions. Agricultural land use has been studied with interest from researchers in several domains such as agronomy, economics, sociology, computer simulation, geography and land use planning with separate focus. The purpose of this review is to give a wider picture of the existing literature around agricultural land use planning to consider the range of tools and approaches used for land use planning, and the implications for developing a simulation tool that supports decision-making. The key theoretical concepts of this research lie at the intersection between land use planning, simulation modelling and the diffusion of agricultural innovation as illustrated in Figure 2-1. These three fields of research are examined in this Chapter to provide the basis for this thesis to tackle the complexity of agricultural land use planning.

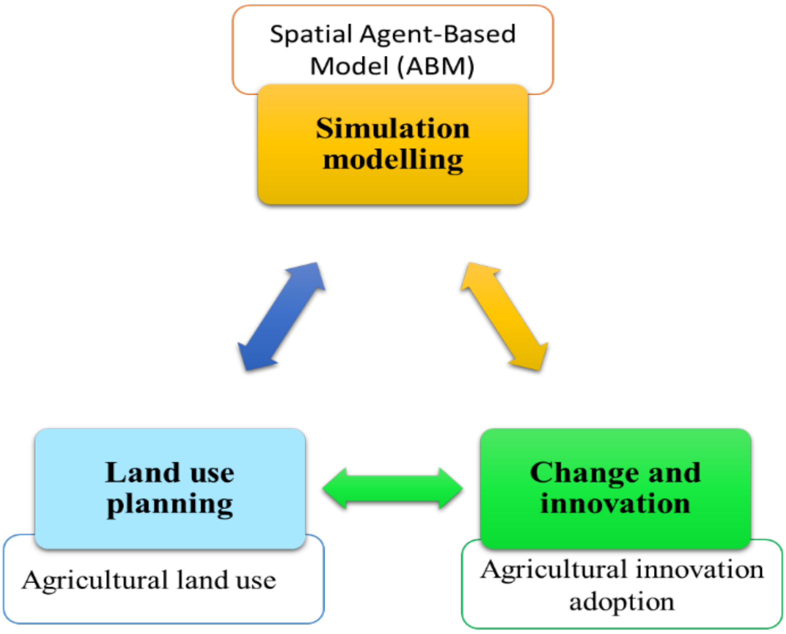


Figure 2-1 Literature review structure

The Chapter begins by looking at land use planning, particularly agricultural land use planning, and the challenges for decision-making on agricultural land and water use in Australia. The review of planning literature is followed by a brief review and summary of adoption of innovation in the context of agricultural enterprises and the implications of change and innovation for land use planning.

Effort has been directed to spatial decision support tools – in particular, geographic information systems (GIS) that can help address the complexity in land use planning. In the next section simulation models and their applications enabled by the agent-based modelling (ABM) approach are discussed, and then GIS and ABM platforms and software are reviewed. The interface of land use planning and GIS is also examined. Key bodies of work in landscape analysis and design are included because of the attention to spatial data and GIS platforms. The discussion follows with the summary of these three concepts and the identification of gaps in the current knowledge.

2.2 Land use planning

Land and water resources are under pressure for food production. Sustaining agricultural efficiency requires managing the use of natural resources in an effective and practical way (Department of Agriculture & Water Resources 2015-2016). In response to challenges and competition for using land resources, land use planning has been promoted as a planning technique for the allocation of the best land use options by international agencies like the United Nations Conference on Environment and Development (Ziadat, Bunning & De Pauw 2017). Land use planning is ‘the systematic assessment of land and water potential, alternatives for land use and economic and social conditions to select and adopt the best land-use options’ (Food and Agriculture Organization of the United Nations (FAO) 1993, p. 1). Land use planning systems most frequently include controlled land use through a zoning system and provide legal certainty to ensure a growing economy and population. A critical point to note is that traditional land use planning is often more passive and less responsive to changing circumstances. In contrast, strategic planning is generally a long-term and comprehensive plan, bringing together social, economic and spatial considerations (Nadin & Stead 2008). Strategic land use planning is an iterative, proactive, dynamic and deliberative process of assessing the future land uses on a regional scale.

Strategic planning in Australia emerged in the 1970s (Buxton et al. 2006); until the 1990s the planning system was very much shaped by the British style of planning (land use planning and regulation). Since the 1990s, Australia has been interested in strategic planning to provide strategies for cities, city-regions, and regions and to create a context for development rather than granting permits (Albrechts, Healey & Kunzmann 2003; Thompson & Maginn 2012). Strategic approaches, frameworks and perspectives for regions became popular in Australia as a response mechanism to continued growth (Albrechts 2006). This was mainly because land use planning is not a practical approach for managing land and water under changing circumstances, particularly at the regional scale (Hersperger et al. 2018).

In Australia, there is a line between strategic planning and land use planning based on the scale of the planning area. Strategic planning is usually at the national or regional level, while land use planning is generally at the level of the municipality and the functional urban region. This different scale of planning system gives rise to a range of conflicts of interests from local land use development to the regional and national level and it is this type of conflict that can be seen in agricultural land use and peri-urban areas (Buxton et al. 2006; Castles 2014). In particular, the challenges of planning for agricultural lands in Australia lie in the growing demand for other uses for agricultural land and water resources such as residential and industrial developments (Schirmer 2018).

There is no single federal planning system in Australia. The six States and two Territories have separate planning systems and jurisdictional characteristics that rely on regulatory tools such as land use zoning and planning regulations (Williams 2012). However, all planning issues need to be considered within the context of the Commonwealth Environmental Protection and Biodiversity Conservation Act 1999 (EPBCA) (Commonwealth of Australia 1999), which can have implications for agricultural land use and proposed changes in agricultural land use.

For the most part, the current Australian planning system sits between British-style statutory land-use planning and regulation, and the more strategic American-style policy interventions (Thompson & Maginn 2012). Statutory planning provides the legal framework for governing land use and assessing development. While statutory planning emphasises regulation, strategic planning considers broader issues or directions and provides guidance through strategic intent – often then implemented by a statutory planning mechanism (Williams 2012). For example, this strategic intent may pertain to the preservation of agricultural land or the protection of land and water resources which might be utilised by agriculture. However, generally speaking within the statutory planning processes, agricultural land is categorised as ‘for agricultural use’, or as a mixed-use zone (i.e. it may be agriculture but may also contain a commercial enterprise – for example vineyard and winery, or as rural -urban interface or peri-urban). Different jurisdictions may label them differently.

There is a wide range of mechanisms, methods and tools for land use planning systems in Australia (Gurran 2011) and each State and the Territories have adopted different methods and tools for preparing regional strategies and planning schemes. Further, alongside statutory planning requirements in Australia, there are other approaches and settings where land use planning has been implemented and which affect rural land use planning in general and agricultural land use in particular. For example, the landscape planning approach and framework has been embedded in the South East Queensland Regional Plan 2005-2026 (Low Choy 2006). In another example, in Western Australia, visual landscape planning provides structure and guidelines to help the plan-making process and seeks to protect landscape characteristics (Western Australian Planning Commission 2007).

2.2.1 Landscape planning

Landscape planning is considered to have been influenced by the work of Ian McHarg and his seminal publication *Design with Nature* published in 1969. This work was the forerunner to designing landscapes based on ecological principles and subsequently the development of land use mapping tools and GIS (McHarg 1992). This catalysed the opportunities for more sophisticated computerised layering – a process used by McHarg, who defines ecological planning as

> that approach whereby a region is understood as a biophysical and social process comprehensible through the operation of laws and time. This can be reinterpreted as having explicit opportunities and constraints for any particular human use. A survey will

> reveal the most fit location and processes. (McHarg 1997, p. 329 cited by Steiner 2012, p. 10)

In 2012, Carl Steinitz, Professor Emeritus of Landscape Architecture and Planning at Harvard University, published *A framework for Geodesign: changing geography by design*. Steinitz' framework is an iterative design workflow for designing and assessing alternative futures of landscape change at different scales and took the thinking around landscape planning to the next level. Steinitz's framework has been put into practice on regional change problems and landscape design in a range of projects around the world. Steinitz argues that

> Geodesign, as an idea, has the potential to enable more effective and symbolic collaboration between the geography oriented sciences and multiple design professions, particularly when they both aim to influence major environmental and social change for the better. (Steinitz 2012, p. iii)

Therefore, geodesign as an iterative design method, demonstrates the potential for better integration of land use planning and environmental science by using geospatial data and simulation models and collaboration among stakeholders.

In Australia, the landscape is a complex cultural and biophysical area (Thackway et al. 2018). It is further complicated by not only significant contrasts in landscape types, but also by highly concentrated human settlement patterns on high quality agricultural land, for example being a relevant case in point where different and competing demands meet. Cognisant of the approaches developed by McHarg and Steinitz along with rapid developments in spatial land/geographic information systems, several States have adopted landscape (ecological) planning for regional and metropolitan-scale planning. For example, Queensland's Sustainable Planning Act 2009 (as amended) is underpinned by the principles of ecologically sustainable development (Low Choy 2018).

Similarly, other agencies responsible for the environment, or land and water resources or mining and/or agricultural activities have recognised the need for land use planning. Alongside design thinking and GIS applications other approaches have been implemented for land use planning. Integrated catchment management (ICM) is a framework that underpins the sustainable management of land and water and biodiversity resources based on community involvement, technical knowledge, organisational structure and policy objectives in the context of water catchment areas (Bellamy et al. 2002). While the ICM approach varies around Australia, and is mandatory in some States, the focus is more on natural resource management.

Other ‘forms’ of land use planning that affect agricultural land use also add to the plethora of planning and regulations with an impact on agricultural land. Since 1980, the Australian Government (excluding local government) has promoted environmental programs and initiative such as Landcare, the Natural Heritage Trust and Caring for our Country (McKenzie 2011). For the most part, environmental and agricultural departments have directed these programs. Landcare Australia became a national program in 1989, and Landcare studies consider a sustainable approach to agricultural land management and the environmental impacts (Landcare Australia n.d.).

Further, the National Action Plan for Salinity and Water Quality (NAP) and the second stage of the Natural Heritage Trust (NHT) are two principal investment initiatives for addressing natural resource management issues in Australia (Australian National Audit Office 2008). Caring for our Country was an initiative that offered multi-year funding to provide certainty for stakeholders with focuses on the sustainable environment and sustainable agriculture (Australian Government n.d.). It is important to note that, while all of these approaches encompass agricultural land, the planning occurs within an environmental framework. This is certainly important, but it does not necessarily capture the decisions made by farmers on land use options.

One of the challenges for measurement of ICM outcomes is that the ecological effects of land use planning and water management will be revealed years after passing policy and plans. For example, numerous land care strategies for the Murray–Darling Basin have been implemented by Australian and State governments since 2000, but issues of declining water quality, salinity and the maintenance of biodiversity have not yet been resolved (Australian Government 2014). Disagreement on conservation and development values between stakeholders, and cross-jurisdictional programs, have placed pressure on the Murray–Darling Basin and changed its landscape (Faith & Walker 2002; Hicks, R 2018; Schirmer 2018). However, within this context, many decisions are being, and have been made by primary producers (farmers) regarding agricultural land all along the Murray-Darling system (Boully et al. 2005).

2.2.2 Australian Collaborative Land Use and Management Program (ACLUMP)

Australia has been a pioneer in systematic surveys of land resources using scientific information system and GIS mapping for natural resource management (Thackway 2018). Although large regional and metropolitan areas in Australia were mapped by the late 1970s, based on the CSIRO[1] methodological approach of environmental (landscape) resource mapping, several regional-scale strategic plans have also been completed by considering economic values over biophysical-landscape values (Low Choy 2018).

Before 1999, there was no consistent national set of land use coding, coordination and standards, and each State and the Territories independently produced a detailed mapping of land use with a variety of coordinate systems and classification methods. By the time of the establishment of the Australian Collaborative Land Use and Management Program (ACLUMP)

[1] Commonwealth Scientific and Industrial Research Organisation (CSIRO)

in 2000, national land use mapping was conducted at two scales (the national scale and the catchment scale). Coordinated land use information informs national policy and planning decisions (e.g. biosecurity), and also provides high-resolution regional (catchment) scale mapping (either 1:25,000 or 1:50,000) for natural resource management (Hicks, R 2018).

The Tasmanian land use mapping program follows the Australian land use management classification (ALUMC) and produces maps at the catchment scale for the State. The land use data are available from the Land Information System Tasmania (LIST), which is an online mapping application managed by the State Government (Department of Primary Industries Parks Water & Environment -Tasmania n.d.-a).

2.2.3 The Tasmanian planning system

In the Tasmanian planning system, the Land Use Planning and Approval Act 1993 (LUPAA) sets out the planning schemes. Following formation of a Planning Reform Taskforce in mid-2014, the Government is reforming the planning system to meet challenges at the regional level and proposes a single planning scheme (The Tasmanian Planning Scheme) for the whole State. The Tasmanian Planning Policies (TPPs) is a comprehensive set of policies and strategic directions for Tasmania’s land use planning system (Tasmanian Government 2018a). The Regional Land Use Strategies (RLUS), which is informed by the TPPs, presents long-term planning goals and strategies for regions, manages land use change and facilitates growth within regions (Tasmanian Government 2018b). For example, RLUS specifies how much land should be allocated for agricultural or industrial use in the North West, Northern, and Southern regions in Tasmania.

Given the current reform in the Tasmanian planning system (Tasmanian Planning Commission n.d.), this study is both timely and highly relevant in its investigation of appropriate tools to assist in decision-making about agricultural land use. This is all the more important given how crucial Tasmanian agriculture is to the State's economy (Eslake 2017), the detrimental impact of climate change (Harrison, Cullen & Rawnsley 2016) and the challenges of land use planning at the State, regional and local levels.

2.2.4 Challenges of land use planning

The relationship between land use science and policy is complex; sometimes policy does not align with the scientific evidence. Policymakers use several forms of 'evidence' or input including (1) systematic and scientific research, (2) program management experience, and (3) political judgment (Head 2008). The policymaking on land and water use is a social and political process, and sometimes is beyond the rational scientific evidence on land use because of other forms of 'evidence' (Dovers & Hussey 2013). Dovers (2018) further describes that a key issue for decision-making on land use is a lack of mutual understanding of the uncertainty and standard of scientific proof by policymakers on the one hand, and political function and public policy by scientists on the other hand.

As Schirmer (2018) suggests, scientific land use decision are more likely to be trusted if policymakers, scientists and other stakeholders agree on the methods of data collection and interpretation of the scientific data. Equally, stakeholders' involvement in the decision-making process can reduce the uncertainty of land use decisions and ensure a shared approach to dealing with land and water use issues (Boschetti et al. 2012; Voinov et al. 2016). Thus, given these circumstances, one approach to tackling the social complexity of decision-making processes is through collaborations among policymakers, land use planners, farmers and other stakeholders.

2.2.5 Agricultural land use planning

From 2000 to the present, regional land use planning in Australia has been better informed through advances in environmental resource mapping. However, there is not strong integration of biophysical and sociocultural information into the land use planning process (Low Choy 2018). Although Australian collaborative land use and management program (ACLUMP) has responded well to land use and land management considerations, there is an increased demand for monitoring and reporting and updating of land use changes. This is especially so in areas that are experiencing rapid land use change such as irrigated agricultural land, peri-urban and coastal areas (Lesslie, Barson & Randall 2008). Effective collaboration between planners and scientists, from the beginning of the planning process and integration of scientific evidence to support land use decisions, were identified as an important factor that strengthened holistic and environmentally based planning practice in Australia (Dovers & Hussey 2013; Low Choy 2018).

Science-informed land use planning, as an alternative paradigm, can be used to establish the priorities and rules for land and water resource by balancing local and regional biophysical, social and economic values (Thackway et al. 2018). Therefore, it is proposed that approaches like geodesign, as an iterative design method, can facilitate landscape planning using geospatial data and simulation models and collaboration among stakeholders. When developed in this way land use information provides the ability to show landscape patterns and track land use change over time. However, there remains a need for better integration of land use planning and environmental science (Thackway et al. 2018).

Planning for agricultural land use necessitates a mixture of considerations and assumptions drawn from statutory planning (legislation and regulation for controlling land use), strategic planning (policy and strategies for the present and future of regional and agricultural land use) and landscape planning (landscape and natural resource management focuses). Figure 2-2 illustrates an agricultural land use planning schematic.

Figure 2-2 A schematic for agricultural land use planning

Serious gaps however still exist, and it is difficult to find examples of where agricultural land use planning *per se* has been well developed. The agricultural landscape in Australia is experiencing considerable pressure from both development and conservation needs and is facing challenges such as climate change, urban encroachment and land degradation. While, as outlined above, there are several different approaches to land use planning that do or can include agricultural land use, an ongoing issue is the layering in of socio-economic data. In agriculture, in particular, this gap is potentially more significant. This is because farmers' behaviours and decisions shape the individual choices they make about the use of land and water resources. The cumulative effects of farmers' actions and behaviours can have far-reaching implications but are largely not well integrated into the land use planning tools.

Challenges of agricultural land use planning

Preserving sufficient and suitable land and water resources for agricultural purposes is an ongoing and ever-present issue and a challenge for land use planning. The separation of regional and local levels of planning systems intensifies a range of conflicts of interest from local land use development such as new industrial dairy farms to regional development issues like water allocation in a river basin. The challenges of planning for agricultural lands in

Australia are contributed to by demand for other uses of agricultural land and water resources. These include demands as wide-ranging activities such as coal seam gas extraction, climate change, and residential and industrial developments (Schirmer 2018).

As the population grows in Australia, urban encroachment into peri-urban areas and agricultural land increases (Sinclair & Bunker 2012). It is essential to balance land use planning to cover the spectrum of natural resource considerations for both agricultural and urban land use and to simultaneously prevent the conversion of agricultural land to urban use. Simultaneously the issue for government and industries is to ensure sustainable agricultural land use policies in the context of drought, extreme weather events and food security.

One of the purposes of strategic land use planning is to provide guidance not only for government agencies, from the regional level to the local level, but also for farmers and landowners (Ponnusamy 2008). Land use classification and crop suitability maps that are developed by government agencies help farmers to plan for their farms by using spatial data and reliable information at the regional scale. Strategic land use planning with an agricultural focus can help to identify significant agricultural areas at the regional level for securing agricultural land and water resources (Department of Primary Industry and Regional Development n.d.).

Agricultural land use planning can also provide strategic advice, information and maps about most suitable crop options (Grose 1999) at the farm level. Using spatial data for agricultural land use planning at the farm level is challenging. First, spatial data of land use becomes sparse when the scale of the maps increases from 1:100000 to 1:25000. Second, the interpretation of spatial data needs knowledge and tools to which farmers might not have access, especially in remote areas. Some studies highlight that those farmers who want to better utilise their farm enterprises consider land capability, the crop options and decision support tools and techniques as necessary inputs for their decision making (Maru 2003; Kahan 2013).

Hitherto, most of the techniques and models used for regional and strategic land use planning have a top-down approach (Pissourios 2014). The top-down approach in planning traditionally tends towards a centralised decision-making process while the bottom-up perspective in planning has a tendency towards a communicative and participatory approach at the local level (Murray, M et al. 2009). This is especially so in agricultural land use. The voice of the people who live in rural and regional communities is often neglected in top-down planning (e.g. statutory land use planning and regulation) and policy-making (Albrechts, Healey & Kunzmann 2003). While agricultural producers are the primary ‘implementers’ of agricultural land use policy and planning, the decisions in the making of policy are likely to be concentrated in the hands of politicians. Farmers as micro-scale decision-makers, therefore, follow agricultural guidelines and instructions. Thus, the involvement of different rural land use stakeholders in the planning process, especially farmers, is one way of bringing relevant data to bottom-up planning approaches, thereby increasing the probability of a prosperous agricultural land use plan (Roy & Ganguly 2009; Koontz & Newig 2014; Cinà & Di Iacovo 2015).

2.2.6 Agricultural land use in Tasmania

Agriculture plays an important role in Tasmania’s economy. The existing agricultural zones have a significant impact on the way farmers visualise the potential of the agricultural landscape and make decisions about the use of their land. Following the current reform in the Tasmanian planning system, the Agricultural Land Mapping Data project was commissioned to classify Tasmania’s existing and potential agricultural land use (Department of Justice Planning Policy Unit, Macquarie Franklin & Esk Mapping and GIS 2017). The mapping of potential agriculture land use was done by the Department of Primary Industries, Parks, Water and the Environment (DPIPWE). A key dataset for this was Enterprise Suitability Mapping

(Department of Primary Industries Parks Water & Environment -Tasmania n.d.-b). Localised climate data, topographical parameters and digital soil mapping were analysed to identify existing and potential land use for a range of agricultural enterprises.

Base on the mapping layer (mapping layer 1) that is available on the Land Information System Tasmania’s website (the LIST), around 22% of the area of the island state of Tasmania has the potential for agricultural production. Agricultural Land Mapping Project as a land use planning tool focused on multiple aspects of biophysical conditions of agricultural land. The mapping can assist planning authorities in identifying and mapping Agricultural and Rural Zones. However, it did not take into account the socio-economic process for analysing and producing the mapping layers of the Agriculture Zone and did not consider the cumulative impacts of individual farmer decisions on land use change.

2.2.7 Agricultural land use change under irrigation expansion

Agricultural land use planning focuses on agricultural land and water resources to both protect and expand their use for agriculture and food businesses (Department of Primary Industry and Regional Development n.d.). One strategy to secure water in agricultural land use is to expand irrigation storage supplies in the region. Irrigation, as a controlled application of water supply, helps farmers to grow, maintain and intensify crop production, especially during drought periods. However, the expansion of irrigation in a region can affect multiple stakeholders and the community.

In Tasmania, the broad perspective is to make the island’s water secure for agricultural sectors (Department of Primary Industries and Water 2008). The introduction of a new irrigation scheme requires careful consideration of different stakeholders such as farmers, local government, State irrigation bodies and the food processing industry. Thus, in Tasmania, a chief consideration for deciding on irrigated land-use expansion has tended to concentrate on how to attract investment by pre-selling water access, rather than land use as affected by farm managers.

Tasmanian farmers' considerations focus on how they can improve water-use efficiency (dry matter produced per unit evapotranspiration) to sustain more agricultural production (Tasmanian Irrigation 2012) and to maximise their return on investment balanced against expenses related to the costs of water and the infrastructure needed to use it. For local communities and local governments in Tasmania the focus is more likely to be on the co-dependence between agricultural products and irrigation and potential economic growth and sustainability for regional development (Tasmanian Food Security Council 2012). Therefore, different biophysical, economic, social and political factors influence the implementation of new irrigation at the regional scale and the adoption of an irrigation scheme by farmers at the farm scale. Implementation of change involves not only macro-scale decisions, but also micro-scale decisions by farmers with the chief consideration being whether to purchase water.

One approach to tackling the social complexity of agricultural land use planning is through the development of models to help simplify complex issues and include a range of different considerations from multiple stakeholders. If the stakeholders can trust the process of data collection and are involved in the process of model development, then the model and the result of the simulation has the potential to be useful for assisting stakeholders' decision-making (Wallace, Geller & Ogawa 2015).

The introduction of change, such as an irrigation expansion strategy, has direct and indirect impacts on farmers' decisions on the type of crops and subsequently on agricultural land use patterns (Belaqziz et al. 2016). Farmers' decisions on investment in irrigation infrastructure on their properties not only changes their practice and the productivity of their farms, but also changes the pattern of agricultural land use in the region. A further factor in agricultural land use planning centres on the rate and kind of change – often seen as the adoption of innovation – which is an added complexity in the planning process. This points to the need to include an understanding of the process of irrigation adoption decisions by farmers. Because irrigation expansion was introduced relatively recently in some regions of Tasmania, the impact of irrigation on land use could be considered as the introduction of new technology and a new farming system approach. Thus, the following section considers the factors that affect how new ideas and technology are adopted by farmers as the end-users who are the main stakeholders and how the adoption decisions can be diffused across the farming landscape.

2.3 Innovation in agriculture

Agricultural land use planning at the farm level is, in effect, carried out by farmers and is generally motivated by the optimisation of profit from the available resources (Fresco et al. 1994). The adoption of an agricultural innovation, such as irrigation, affects land use planning at both the macro and micro level. It is an important change in the agricultural landscape and certainly important for land use planning in Tasmania.

2.3.1 Farmers' decision-making

Understanding how farmers make decisions is important because multiple factors influence their crop choice and land use plan and subsequently, the cumulative impacts of farmers decision change the agricultural landscape. Therefore, understanding of farmers decision-making process and the influential factors that drive their decision can assist to manage the agricultural land use more effectively.

As Ilbery(1977) suggested, there are multiple factors (socio-personal, economic and biophysical) with different level of uncertainty and complexity that affect farmers decisions and behaviours. The influential decision factors can be varied among subsistence and commercial farmers (Greig 2009). Farmers' behaviour are dynamic in a complex agricultural system (Feola & Binder 2010). Farmers in different regions could respond differently to innovation and significant changes such as the introduction of a new irrigation scheme. For example, Long (2013) describes farmers personality types, the level of educations and their intuition affect their decisions on crop choices and agricultural enterprise. The results of a survey of poppy farmers in Tasmania (Macquarie Franklin 2013) revealed that higher price of poppy, better irrigation infrastructure, more reliability, better yield and more irrigation water the influential factors that affect farmers decisions to grow more poppies. Therefore, consideration of the influential decision factors is necessary in agricultural land use planning under changing conditions.

2.3.2 Diffusion of innovation

The seminal study by Everett Rogers, *Diffusion of Innovation* (2003), explains how farmers adopted agricultural innovation in a rural community of Iowa in 1957, providing data and insights on what is now referred to as the theory on the diffusion of innovation. The concept of innovation diffusion describes how a new idea, practice or object that is perceived as new by an individual or group (or organisation) diffuses and spreads over time through a specific social system. Diffusion is defined as 'the process by which an innovation is communicated through certain channels over time among the members of a social system' (Rogers 2003, p. 5). Figure 2-2 shows the rate of adoption and the distribution of adopter categories over time. The categories include: Innovators who adopt quickly (2.5%), Early Adopters (13%), Early Majority who follow the Innovators (34%), Late Majority who have a sceptical awareness about change (34%), and finally the Laggards (16%) who are bound by tradition and are conservative (Rogers 2003). This is a generic parameterisation that may slightly change under different circumstances.

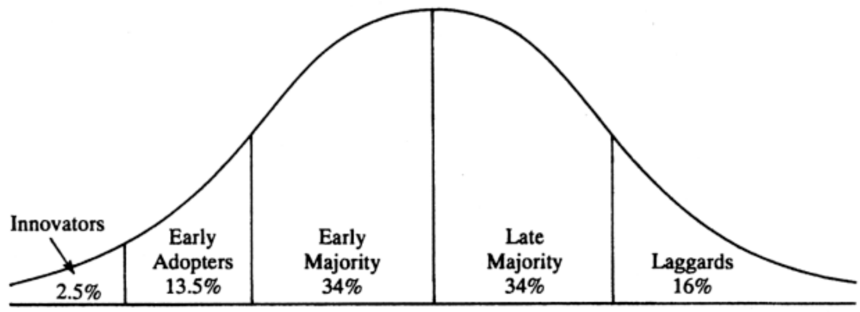


Figure 2-3 Adopter categorisation on the basis of innovativeness (adapted from Rogers 2003)

The adoption of innovation has been studied widely in different disciplines including agricultural science, marketing and communications (Ryan & Gross 1943; Berger 2001; Rogers 2002; Kuehne et al. 2011; Zhang, Gensler & Garcia 2011). During recent decades, most of the diffusion studies have focused on one of two levels: an individual level (Mitra, LaFrance & McCullough 2001; Venkatesh et al. 2003) and an organisational level (Tanoglu & Basoglu 2006). Two types of innovation-decision models have emerged: the customer adoption decision model and the organisation adoption model (Wright, V 2011). As most farms are micro-businesses or non-employing businesses, farmers' adoption of the innovation-decision model is more like the customer adoption decision model rather than the organisation adoption model (Diederen et al. 2003). This means that farmers are likely to decide on the adoption of innovation based on their desired goals and personality (Schnelle, Brandstätter & Knöpfel 2010) rather than on formal structures and procedures for investing in 'new technology' as would occur in an organisation. However, most farmers, like organisations, adopt an innovation (Wright, V 2011) when they have clear information and understanding of costs and the outcomes (Barr et al. 2008), suggesting that their adoption model is also similar to the organisation adoption model. Therefore, a diffusion model of agricultural innovation seems to draw on a middleware approach of customer and organisational innovation decision models (Wright, V 2011).

Pertinent to the aforementioned literature, the diffusion of innovation theory provides insights for understanding how farmers' decisions on agricultural innovation can significantly change the land use patterns. The diffusion of agricultural innovation can be understood through the tracking of farmers' decision-making (Conroy, Snapp & Pound 2008). Previous studies have shown that farmers decide on the adoption of new practices based on both a series of profitable factors and components and on some other factors that are not motivated by profit (Vanclay 2004; McKenzie 2011; Vanclay 2011). The nature of agricultural innovation (e.g. new crop type or new machinery), the type of farm enterprise (e.g. a dairy farm or potato farm) and the decision-makers' personality and interaction (farmers' tendency to adopt new crop), all influence how agricultural innovation diffuses across the landscape.

Two possible gaps in the previous literature were identified. First, most of the diffusion studies regarding agricultural innovation were quantitative (Ruttan 1996; Dilaver 2015; Hazelman 2017) and mainly concentrated on a cumulative number of innovation adopters and temporal aspects of adoption of innovation. In recent decades, however, studies have considered diffusion of agricultural innovation as a complex process that might not always be rational, with informed decisions based on costs and benefits of agricultural innovation adoption (Heckbert 2010). Second, the interdependency of the geographical location of the farm land (e.g. land use) and farmers' adoption behaviours have rarely been studied directly. This research seeks to accommodate this kind of interdependency between spatial characteristics (e.g. land and crop suitability) and farmers' adoption behaviours and decisions and investigate the interdependence between geographic and biophysical conditions that determine farmers' adoption behaviour and decisions. This research considers how farmers' decisions on adoption of irrigation change the land use pattern in a region.

2.4 The issue of complexity

In the above Section, issues relating to land use planning in general and to agricultural land use planning specifically have been discussed. The discussion shows that while farmers decide on land use at the farm scale, their decisions ultimately also influence broader land use change (Gutzler et al. 2015). Thus, the relationship between a farmer's decisions and how they respond to innovation (e.g. irrigation) and agricultural land use change are central to this research. But it is also clear that successful planning of agricultural land use requires consideration of how scientific evidence supports not only the values of different stakeholders but also addresses scientific assessment criteria. Agricultural land use planning and decision making is complex.

This complexity points to the need for development of a model-based approach that accounts for the multiple biophysical, social and political drivers. One approach, now widely used at the strategic level, is to create land use change scenarios that are developed and analysed using simulation techniques. Could simulation techniques be developed as a tool for analysing how the introduction of irrigation influences farmers' decisions on adoption? Such a simulation model would be expected to simulate the complex processes of agricultural land use change outlined above. The next Section explores the complexity theory, the nature of the simulation, and how they have been used in land use planning.

2.4.1 Complexity theory

There are many different definitions of a complex system. Zeng et al. (2017, p. 3) suggest that complex systems 'consist of a large number of components that interact with each other to produce nontrivial phenomena that cannot be explained by analysing the individual constituent elements'. Complexity theory as a scientific theory focuses on how a nonlinear and highly complex system that has many components, such as a region or human society, emerges into a coherent form and adapts deliberately with its environment (Manson 2001; Sonnessa 2004). Complexity theory is a theoretical foundation for simplifying a complex system and can be applied to social phenomena to explain the emergence of a pattern of human actions.

Cities and regions are complex systems (Wilson 2002; White, Engelen & Uljee 2015). Cities and regions are a representation of many diverse and autonomous components that have nonlinear interaction and dynamic connection. In this context, complexity theory has emerged as a common approach in urban and regional planning in the last thirty years (De Roo & Hillier 2016) and has been applied to the modelling and simulation of land use planning (O'Sullivan 2004; Richiardi et al. 2006). The urban mobility simulation model (Behrisch et al. 2011), and studies of effects of land markets on land use using the FEARLUS-ELMM model (Polhill, Parker & Gotts 2008) are examples of using simulation to tackle the complex problems in urban and regional studies. Similarly, geographers, social and environmental scientists, along with urban and regional planners, are interested in how complexity theory might assist in modelling and simulating a spatially extended human-natural system (Walsh et al. 2008). Given the complexity of agricultural land use planning, it is proposed that using a simulation model can help to simplify the complexity of human-natural system interactions.

2.4.2 Simulation literature

The purpose of model development is to simplify the complexity of the real world by deciding what particular aspects need to be modelled (depending on the circumstances) and what do not. O’Sullivan and Perry (2013, P.3) define a scientific model as ‘a simplified representation of a system under study, which can be used to explore, to understand better or to predict the behaviour of the system it represents’. Simulation is a computer-based representation of a system and its process (Axelrod 1997). Simulation models are computational programs that mostly represent the model of the real-world system with a different scale of time and space (Sonnessa 2004; Lin & Wooley 2005). In this way it is possible to build models though formal languages in computer environments, thus allowing experimentation in a ‘virtual laboratory’ to produce pseudo-empirical results (Gilbert & Troitzsch 2005).

Computer simulation relies on equation-based and mathematical modelling in natural science and engineering, while social science simulation focuses on understanding human society and interactions and is challenging to be modelled mathematically. Nevertheless, computer simulation can be used for understanding some particular social phenomena or making predictions such as forecasting election results (Laver & Schilperoord 2007). Most recent developments in artificial intelligence (AI) and agent technology have influenced the simulation of human behaviour and interactions in the environment (Gilbert & Doran 2018).

The first example of using computer simulation with a focus on human behaviours dated from the 1960s (Abelson & Bernstein 1963) and coincided with the first use of the computer in university research (Gilbert & Troitzsch 2005). From the 1980s to the late 1990s, simulation models focused on policy concern and prediction (e.g. taxation policy) and less on understanding social processes (Orcutt, Merz & Quinke 1986; Harding 1996). In the 1990s, simulation models in social science changed rapidly because of the development of multi agent-based models (ABM) and techniques imported from nonlinear dynamics and artificial intelligence research (Gilbert & Troitzsch 2005).

Axelrod (1997) classifies the purposes of using simulation into seven categories namely prediction, performance, proof, training, entertainment, education, and discovery. Prediction, performance and proof are common uses of simulation. If the model accurately mimics the dynamic of the system, its behaviours and interactions, then the simulation can pass the model through time to predict the future or to perform specific tasks or provide evidence of proof (Vallverdú 2014). Simulation has subsequently been used to train people; such as flight simulators for pilots, or to educate users about the relationship of components and variables. Simulation can be designed to discover phenomena and understand the relationships, principles and patterns of human societies in a virtual environment (Gilbert & Troitzsch 2005).

The majority of prior research has applied simulation models to investigate human-environment interactions. ABM simulation provides a ‘virtual laboratory’ for testing the hypotheses of human decisions. Given the applications to date, it is proposed that ABM simulation could be used in agricultural land use planning to simplify the complex representation of the farmers’ decision-making process and their interaction with their farm land.

2.4.3 Purposes of using simulation in this study

Developing and testing a physical field trial of policy and/or the experimentation of scenarios in ‘the real world’ is costly, time-consuming and sometimes impractical (Wallace, Geller & Ogawa 2015). The complexity of agricultural land use planning, and the growing application of simulation as a method for testing scenarios suggests that simulation is a suitable method to understand land use change such as irrigation expansion. Using a simulation model, especially agent-based simulation, affords an opportunity to explore agricultural scenarios and derive new insights and understanding of the social complexity and economic processes that underpin the emergence of macro-scale land use patterns and the relationship to the actions of individual farmers (Shahpari & Allison 2017).

Simulation is used in this research for three main reasons. Firstly, it can accommodate the generation and analysis of multiple agricultural scenarios, and processes such as the adoption of agricultural innovation can be analysed through computer simulation. Secondly, the process of farmer-land use relationship can be simulated in the context of human-natural system interactions. Thirdly, the emergence and availability of macro-scale patterns of regional land use in the virtual environment (e.g. GIS platforms) allows policymakers, planners and other stakeholders to explore the consequences of change (such as irrigation expansion policy) on regional agricultural land use.

2.5 Agent-Based Modelling and simulation

As highlighted in earlier Sections, human decisions and behaviours are complex and usually based on incomplete information. Indeed, the notion of human agents as a rational, self-interested economic agent has been challenged by experimental economics research (Simon 1982; Reeson & Dunstall 2009; Heckbert, Baynes & Reeson 2010). These findings reveal that a human decision can change under new circumstances and sources of new information, allowing for dynamic behaviours. The research shows that people usually make decisions with limited time and information, without calculation and optimisation of alternatives, and tend to use their previous experiences to simplify the complexity of the decision-making process (Reeson & Dunstall 2009). This suggests that good human decision-making is as rational as possible within cognitive constraints.

Experimental economics has fostered interest in applying ABM simulation – where an agent is the individual decision maker. ABM represents complex systems by modelling individual decision-makers' behaviour and interactions within the simulation (Heckbert 2009) and in this way ABM is a suitable approach for simulation of a complex socio-economic system (Helbing & Balietti 2011). The ability of ABM to represent human decision-makers as autonomous agents also allows for computational experiments of human behaviours, social interactions and emergence patterns in the context of agents' limited resources (Gilbert & Doran 2018).

Further, the applicability of ABM in computer simulation positions allows it to be used to understand a human-natural system within the context of land use science and geography

(Parker, DC et al. 2003; Schreinemachers & Berger 2011). This can be achieved by the integration of spatial data and ABM, altering the parameters and visualising the simulation outcome across a range of different conditions (Crooks & Castle 2012).

2.5.1 Spatial ABM

Historically, ABM as a computer simulation was used to simulate human agent decisions within the broader context of land use (Berger 2001; Parker, DC et al. 2002; Schreinemachers & Berger 2011). However, little research has focused on an agricultural land use change and human decision models. ABM has had wide use in urban and regional planning in exploring land use change and economic choices (Brown, D et al. 2005; Batty 2007; Baynes & Heckbert 2009). More recently, there have been a large number of successful ABM applications (Johnston 2013) in complex environmental modelling often referred to as spatial ABM. In spatial ABM, the agent interacts with its environment and alters the attributes of its current location by exploiting resources in its environment. The agent also interacts with other agents to modify its state of location (e.g. changing the land use) during the time or, perhaps merely updates its current location (O'Sullivan et al. 2012).

The value of spatial ABM is that it is not only flexible for the handling of time but also relatively appropriate for representing changes in space (Brown, D et al. 2005), allowing it be used in different types of studies. Parker et al. (2003), for example, studied land-use and land cover changes by combining spatial information with dynamic agent-based models. Some spatial ABMs have been developed to simulate human-environment interaction, natural resource management and land use change (Bithell & Brasington 2009; Iwamura et al. 2014; Castilla-Rho et al. 2015). Furthermore, the impacts of policy have also been investigated through spatial ABM, such as in education planning (Harland & Heppenstall 2012), in the diffusion of innovation (Berger 2001), and in climate adaption (Berger & Troost 2014).

2.5.2 Agents

The key concept in ABM is an agent. The concept of agency usually applies to goal-directed human action and intervention. Generally, the concept of agency in a computer program is weaker than human agency because of the complexity of human decisions and behaviour (Wooldridge & Jennings 1995). That said, computational entities called ‘agent’ have some notions of agency such as autonomy, social ability, reactivity and proactivity as well as some level of intentionality (Jennings & Wooldridge 1995).

An agent, as a goal-oriented entity, represents a decision-maker in the agent-based model (Johnston 2013). As Batty et al. (2012, p. 2) note, ‘agents generate actions that occur in time as well as space, that influence their wider environments and that cooperate as well as conflict with one another over the use of space’. From an object-oriented point of view, agents are self-directed entities. Agent behaviour in ABM is defined as exercising choice among available alternatives to achieve defined goals (O’Sullivan et al. 2012). The complexity of agent action can range from simple activities composed of one instruction to complicated learning algorithms enhancing ABM built-in flexibility (Johnston 2013).

Defining many agents in a population and generating a sense of their diversity is the power of the agent paradigm. Agents could be the people of/in the place, buildings, cars, land parcels, stakeholders, home seekers and decision-makers. According to this definition, agents act individually and make decisions at the micro level, and their behaviour can be tracked over time. Moreover, they have relationships with each other, and their decisions influence their broader environment (Crooks & Castle 2012). Consequently, the agents for this present research are farmers who make decisions about their own farm land based on a set of rules and parameters while they interact with other agents (farmers) and their surrounding environment, and patterns of land use change emerge at the regional scale.

2.5.3 Human-natural system interaction

Human-natural systems are integrated systems in which the interaction of human and landscapes are complex and non-linear. It is also known as coupled human and natural systems (CHANS) (Werner & McNamara 2007; Carter et al. 2014) or coupled social-ecological systems (Walker et al. 2004). The power of ABM simulation is that it allows for feedback between human agents and their dynamic social and environmental conditions (Heckbert 2010). Human agents and their environment can be designed in a computational platform. The ABM simulation of a human subject provides an opportunity to experiment with different types of decision-makers' behaviours and interactions (Barr et al. 2008) under different socio-economic and environmental conditions without the actual involvement of humans.

Spatial ABM is adopted in this research to link the socio-economic human decision model and the biophysical model of land use. Given these circumstances and the characteristics of agricultural land use planning (alluded to in Section 2.2) it is argued that these characteristics can be incorporated into ABM simulation. Such characteristics include:

- heterogeneity of land use,
- farmers as autonomous decision-makers,
- farmers' direct interaction with their land,
- farmers' direct interaction with other farmers,
- farmers' indirect interaction with planning and policy (e.g. market price of crops, irrigation expansion), and
- cross-scale effects from land parcel (micro-scale) to regional land use (macro-scale).

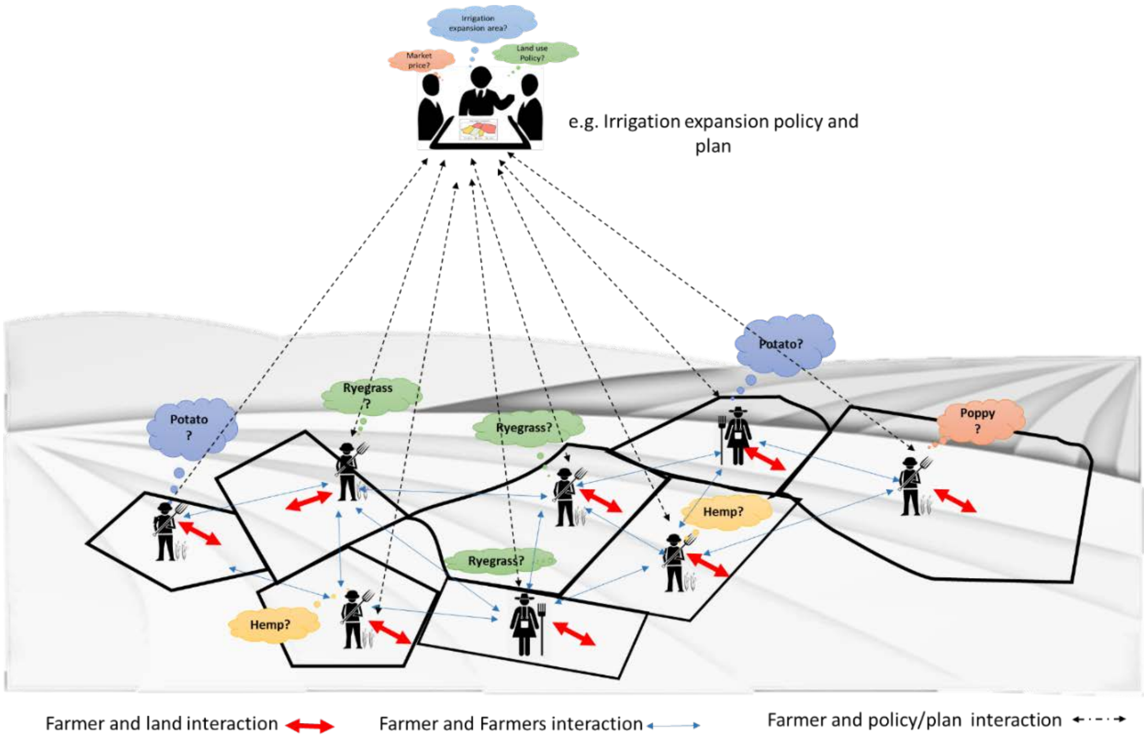


Figure 2-4 Types of farmer interactions

These characteristics align with the aims of this research. For example, farmers can be construed as human agents to have social interaction with each other, such as communication of information with neighbours. Equally, the spatially explicit environment in this study is land parcels where each parcel is held by a human agent (farmer), thereby allowing the human agent to interact with the environment through their farm land. Figure 2-4 illustrates the type of farmer interaction with the land and other farmers. For example, farmer one uses a farming system that is influenced by farmer two, who in turn is influenced by farmer three and policy etc.

2.6 Spatial ABM platform and software

To this point, examination of the literature has highlighted the need for more effective agricultural land use planning. It has also noted that the complexity of farmer decision-making in a dynamic and changing context includes decisions about significant changes such as the introduction of a new idea or opportunity like irrigation. Different farmers respond differently to new ideas, and the argument is that there is a need for better tools to describe the emergence (and impact) of different agricultural land use scenarios based on the behaviour of agents. One such tool is a spatial ABM. A review of simulation studies reveals that over time, spatial ABMs have become more sophisticated, enabling the use of computational simulation to capture human decision-making and interaction with the environment by introducing the idea of the agent into a computer simulation.

Agents, however, are more than people and may include buildings, land parcels, or objects. Importantly, the human agent can be linked to a land parcel, that is, agent data is linked to spatial data. Again, this is an approach well suited to understanding agricultural land use change and opens the way to considering the status of GIS, and some current ABM computational modelling platforms within GIS.

2.6.1 GIS platform and software

In general terms, GIS is the most essential 'method' in quantitative geography, providing an analytical environment for spatial layers in a common coordinate system. Murray (2010, p. 145) describes GIS as 'a collection of hardware, software, and associated procedures to support spatial data acquisition, management, manipulation, analysis, and display'. These characteristics of GIS mean it has become a significant method in regional science, essential for quantifying a range of spatial facts (Overman 2010).

GIS was developed during the 1960s to provide tools for storage and display of both spatial and attribute information in the form of maps, tables and graphs (Jarupathirun & Zahedi 2005). As GIS was integrated with more complex spatial analysis tools, it was adopted for natural resource management in the 1980s, and by the 1990s emerged in business, decision-making and problem-solving (Bracken & Webster 1989; Antenucci et al. 1991). Murphy

(1995) describes the capability of GIS to conduct ‘what if’ analysis and support decision-making activities. The evolution of GIS relied on improvements in technology and the interaction between decision support tools and the decision-maker (Murray, AT 2010). Similarly, Jarupathirun and Zahedi (2005) argue that the visualisation and analytical capabilities of GIS make it useful and efficient for spatial decision support systems (SDSS). Recently, GIS-based SDSS has been applied across many disciplines, professions and organisations, emerging as a significant instrument for understanding the impact of different spatial decisions including business (Thrall & Fandre 2003), participatory planning (Talen 2000), agent-based modelling (Sengupta & Bennett 2003), urban growth (Lee et al. 2002), and water demand (Pimpler & Zhan 2003).

In general terms, the significant components of GIS are data acquisition/input, management, manipulation, analysis, and display. Although GIS is associated with statistical and quantitative spatial analysis, it also relies on non-quantitative methods. Mixing quantitative and qualitative methods with the geospatial analysis in GIS has created the ability to visualise and investigate social and environmental phenomena that cannot be analysed by traditional statistical techniques (Pavlovskaya 2009). A better illustration of this was provided by ESRI Inc. (n.d.) which, in 1999, developed sketch-mapping ArcGIS software, to visualise, analyse, and interpret spatial data. Further, ArcGIS software helps to understand the relationships, patterns, and trends that are tied to spatial data (Sheppard 2001). Increasing innovation in technology such as the aforementioned GIS software, along with robust methods of computation and handling agents’ data to build models, suggests that agent-based modelling in a geographical system is possible and timely. Thus, the relationship between GIS technology and ABM provides a suitable platform for this research by providing the potential for a realistic and appropriate geographic representation of simulation output.

2.6.2 ABM platform and software options

Having established an argument for an ABM and GIS platform, it is also important to consider the options of how GIS and spatial data can be linked to ABM. Considerable inroads have been made in the development of appropriate software to support and enable this kind of platform. There are many simulation systems and appropriate associated software for developing ABM that are capable of integration of GIS. GIS as a platform brings all of the spatial relationships into an integrated form and ABM has the characteristic of representing decision-making entities (agents) and their interaction. The integration of GIS and ABM can boost the advantages of both approaches (Brown, D et al. 2005).

There are four key relationships between agent-level processes and spatial data that may influence the integration of a dynamic GIS database and an ABM process model. These are: identity relationships, causal relationships, temporal relationships, and topological relationships (Johnston 2013). Based on these relationships, there are three possible approaches for integration of ABM and GIS and developing a simulation model. These approaches are: (1) ABM-centric approaches that involve the use of software libraries of GIS functions within ABMs; (2) GIS-centric approaches that have implemented ABM functions and models within a GIS system allowing such models to run interactively within the graphical user interface of the GIS package; and (3) middleware approaches that are centred on both ABM and GIS for developing software to handle identity and causal relationships between agents within an ABM environment, and the temporal and topological relationship (spatial features) within a GIS environment (Brown et al., 2005; Brown and Robinson, 2006). Table 2-1 sets out the features of some platform and software options for developing a simulation model by integration GIS and ABM data.

Table 2-1 GIS-ABM platform and software

Platform/software	**Features**	**Example**
Swarm	An open source ABM simulation and has been used to develop spatial models	Pedestrian simulation in an urban centre (Haklay et al. 2001) and crowd congestion (Batty, Desyllas & Duxbury 2003)
MASON (Multi-Agent Simulation Of Neighbourhood)	A multi-agent simulation library in Java and has been used for spatial modelling	Kennedy et al. (2010) developed spatial ABM within MASON simulation to explore farmer and herdsmen conflicts
The Recursive Porous Agent Simulation Toolkit (Repast)	A free and open source agent-based modelling and simulation platform	for the spatially explicit model of residential segregations (Crooks 2010) and pedestrian evacuation (Castle 2007)
NetLogo	A multi-agent programmable platform	The emergence of territories and settlements by Graham (2006) and the demand for residential housing by Fontaine & Rounsevell (2009)
Agent Analyst	An open source and free software that integrates the Repast ABM (North et al., 2006) within ArcGIS Software (Johnston, 2013)	Spatial simulation of street robbery by Groff (2007), the residential solar Photovoltaic diffusion by Robinson et al. (2011)

As shown in Table 2-1, Swarm, MASON, Repast, and NetLogo are ABM simulation platforms, all of which can be used for developing spatial ABM of a complex system and can be adopted for agricultural land use planning (Crooks & Castle 2012). Although these platforms are useful in developing spatial ABM, they do not visualise the outcomes of simulation in ArcGIS display for each time step of the simulation (Johnston 2013). Given that in this research the intention is to investigate the interdependency between agricultural land use change (GIS data) and farmers' adoption behaviours and decisions (ABM process) it is proposed that the platform/software that has a middleware approach is more appropriate for this purpose. As Agent Analyst focuses on the middleware approach, it can automatically create agents from GIS layers, which makes it a useful software for the development of a simulation model to explore the effects of different agricultural scenarios.

2.6.3 Agent Analyst

Agent Analyst is an open source and free software that integrates the Repast ABM (North et al., 2006) within ArcGIS Software (Johnston 2013). Agent Analyst links the object-oriented ABM and ArcGIS software systems and incorporates ArcGIS functions into an agent model which helps to analyse simulation outcomes. Agent Analyst provides more flexibility for a model developer to have direct access from the ABM model and coding environment to a GIS database (vector-based and/or raster-based database) and a visualisation environment. These characteristics of Agent Analyst software address many of the issues for linking to ABM and GIS in simulating agricultural land use change. The evidence from different studies that have employed Agent Analyst software (Groff 2007; Johnston 2013; Robinson, SA et al. 2013) suggest that it can adequately represent both the complex spatial structures in GIS and the rich dynamical processes of ABM.

Agent Analyst software is employed in this research as being optimal to handle the relationship between human agents (farmers) within the ABM platform and the spatial relationship of lands (farm land parcels) within the GIS platform. For this research, Agent Analyst offers a way of simulating human decision-making on agricultural land use by taking advantages of ABM within the GIS platforms.

2.7 Identification and integration of key concepts

This research focuses on the development of a useful simulation tool that can assist in agricultural land use planning. To address this issue, three key areas of prior research were identified: (1) land use planning, (2) diffusion of innovation, and (3) simulation models.

Several issues were identified in the literature pertaining to agricultural land use planning in Australia, in particular the loss of productive agricultural land and transition and change arising in irrigated agriculture. Some specific aspects of this issue for Tasmania were also highlighted. A number of researchers have pointed out how a combination of technology, scientific methods and cross-disciplinary collaboration are key requirements for informed decision-making in regards to land use planning (Lesslie & Mewett 2013; Lawrence et al. 2018). Others, e.g. Clancy, Bryan & Guru (2018) indicated that there is a growing demand for information, technologies and modelling approaches to improve the analytical power of future land use planning. Specifically, it was found that Tasmania's planning system, recently reformed, provides an opportunity for investigation of up-to-date scientific information and simulation tools to assist decision-making about land use. The implications of the aforementioned literature point to a useful context within which to position this research.

The literature on the diffusion of agricultural innovation suggests that a very suitable approach is the use of middleware modelling of farmer adoption, which can accommodate and incorporate both customer and organisational innovation decision models (Wright, V 2011). The literature also reveals that the adoption of change and/or innovation such as irrigation is a complex decision, as farmers consider not only their desired goals and budget plans but also the social values and social norms of their community (Sutherland et al. 2012). Significantly, they need to consider the uncertainties and the risk of investment associated with any new irrigation scheme. What can be established therefore is that a first step in developing a simulation model is to investigate farmers' decision-making processes and identify the factors that might play a key role in the adoption of agricultural innovation. These factors emerge as key in modelling or simulating farmers' social and economic decisions.

Further, the complexity of farmer-land use interaction reinforces the need for a simulation model that takes into account a farmers' decision model, best accommodated within an ABM platform and linked to the spatial and biophysical data held within a GIS platform. Agent Analyst is identified as suitable software to simulate human decision-making on agricultural land use by taking advantage of ABM within GIS platforms.

2.7.1 Identified knowledge gaps

It is proposed to develop an ABM simulation model to evaluate how irrigation policy and scenarios affect agricultural land use over time. However, it seems that while much of the existing research has sought to examine how land use changes over time, the majority of studies focus on urban land use and little research has been conducted on agricultural land use futures; in spite of pressures on agricultural land use. Table 2-2 illustrates that through the analysis and review of literature relevant to agricultural land use planning it is possible to identify several key gaps in our understanding. This study therefore seeks to build on current research and utilise those findings, tools, methods and software as a platform to address specific gaps as they relate to agricultural land use planning.

Table 2-2 Summaries of the literature review

Research field	Category	Gap	How to fill the gap?
Land use planning	Agricultural land use	Stakeholders' (farmers') decision model and human-land use interaction are not at the centre of the land use modelling approach	Develop scientific bottom-up simulation model and scenario tools to meet the requirements of multi-stakeholder groups
Diffusion of innovation	Adoption of agricultural innovation	Most of the agricultural innovation studies did not focus on the spatial factor of adoption of agricultural innovation	Focus on the farmers' innovation-decision model because the nature of agricultural innovation (new crops/livestock adoption) is different from technology adoption. Integrate an ABM with GIS functionality to simulate the diffusion of agricultural innovation
Simulation	Spatial Agent-Based model (ABM)	Most of the ABM platforms do not automatically create agents from GIS layers and do not visualise the outcomes of simulation in ArcGIS display for each time step	Use Agent Analyst software and vector-based instead of a raster-based technique Displaying the result of simulation in the ESRI ArcGIS

To that end, this study investigates the interdependence between geographical and biophysical conditions that determine farmers' adoption behaviour and decisions. For example, the impact of a farmer's decision on irrigation will change their agricultural practice and subsequently change the land use pattern over time. Developing a simulation model of farmers' decisions offers valuable insights into land use change. Spatial ABM is a simulation model that links spatial data with a human decision model and allows both the use of vector-based data (instead of raster-based data) and also allows displaying the result of simulation in the ESRI ArcGIS software. This research develops a spatial ABM simulation from the 'bottom-up' as a means to examine the implications for farmers' decisions around crops and commodities and land use and the implications for regional land use planning. It also affords an opportunity to refine and sharpen the applicability of simulation to gain more nuanced understandings of agricultural land use and changes in its use over time.

2.7.2 Integration of key concepts

This Chapter began by articulating the key challenges within agricultural land use planning. Table 2-2 summarises some key gaps in regards to managing agricultural land and land use change. Agricultural land use is under pressure but presents a challenging dilemma. Individual farmers make decisions about different crops and use of land shaped by a number of factors including innovation, and simulation can assist farmers to understand the spatial, social, economic and environmental consequences of those decisions. Simultaneously those decisions also affect impact and change on across the agricultural landscape which also need to be understood in order to improve land use management and agricultural land use policy.

This raises a question of how best to address these challenges. Figure 2-5 summarises the synthesis of key concepts in response to these challenges and adopted as the platform for this research. It is worth highlighting that the complexity and interdisciplinary nature of planning problems – especially agricultural land use planning – is what this study attempts to address. One way to overcome the complexity of agricultural land use planning is to employ spatial

ABM to integrate a complex series of environmental, economic and social systems including farmers' decision-making.

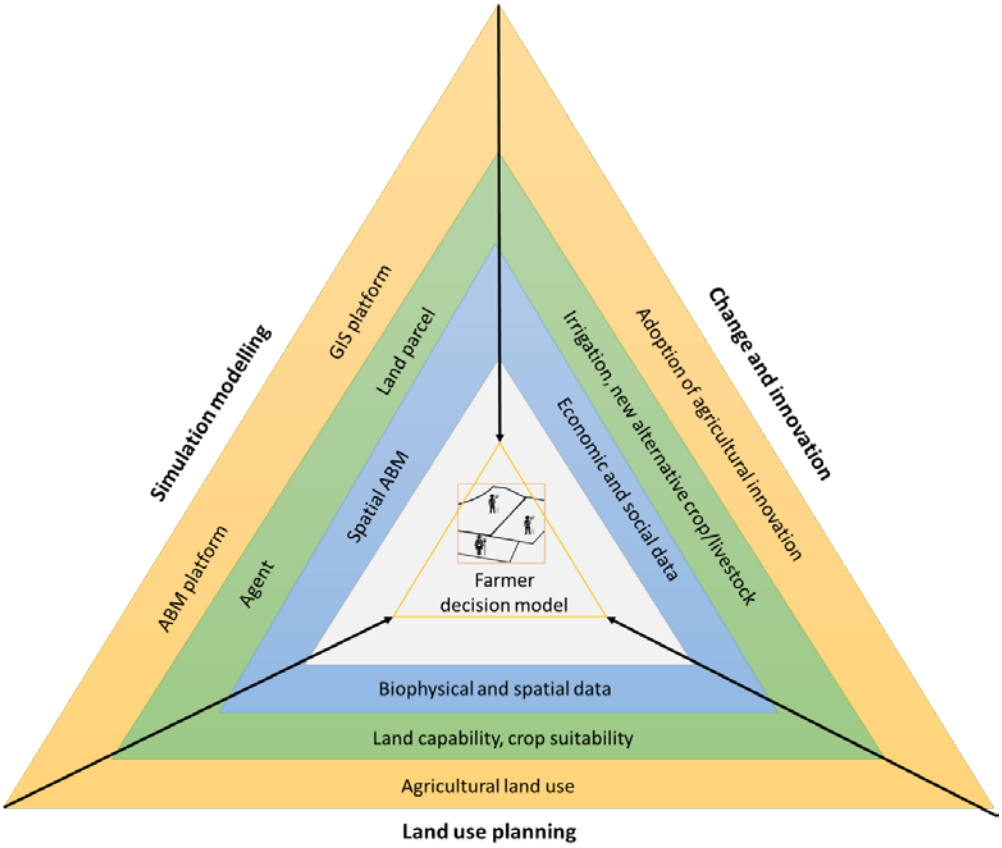


Figure 2-5 Abstract integration of key concepts – natural and human systems through simulation

Previous studies demonstrate that the advances in spatial technology and scientific modelling approaches improve monitoring and reporting of land use change (Hicks, W, Viscarra Rossel & Tuomi 2015). ACLUMP, and the Multi-Criteria Analysis Shell for Spatial Decision Support (MCAS-S) are examples of the usage of spatial information and modelling approach for land use and land management practices (Hill et al. 2005; Lesslie & Mewett 2013). However, current biophysical models of land use are generally top-down in their approach and do not link micro-level human decision data to the biophysical and land use data in GIS.

In response, this research aims to develop a simulation model to understand better how micro-scale decisions (the farmer's decision) affect land use change in a region. The particular focus of this research is to build a simulation model of land use and water use by involving various stakeholders and integrating qualitative and quantitative data.

This research aims to examine the integration of social, environmental and economic data (both quantitative and qualitative) in a spatial ABM. Spatial ABM as a simulation tool is identified as an effective way to address a range of barriers like the cost and time of data collection that affect or limit empirical studies. Further, this study develops a spatial ABM based on stakeholders' insights on a farmers' decision model to examine previously identified barriers to building integrated models. Spatial ABM also can be used as a 'virtual laboratory' to undertake computational experiments with a human decision on agricultural land and water and investigate how agricultural land use changes over time. In the next chapter, Chapter Three, the research methodology and methods of collecting quantitative and qualitative data to address the research questions are outlined.

Chapter 3: Methodology

3.1 Introduction

This Chapter presents the methodology and research design of the study along with the methods used for data collection and data analysis. The Chapter begins by outlining the philosophical basis underpinning the research design and method selection.

Overall, the methodology comprises three intersecting stages that allowed for a mixed-method research design and guided the selection of the methods and techniques needed to examine the research questions. As Figure 3-1 shows, the three distinct stages include conceptualising the farmers' decision model, programming a spatial ABM based on farmers' decision model, and simulation of different agricultural scenarios:

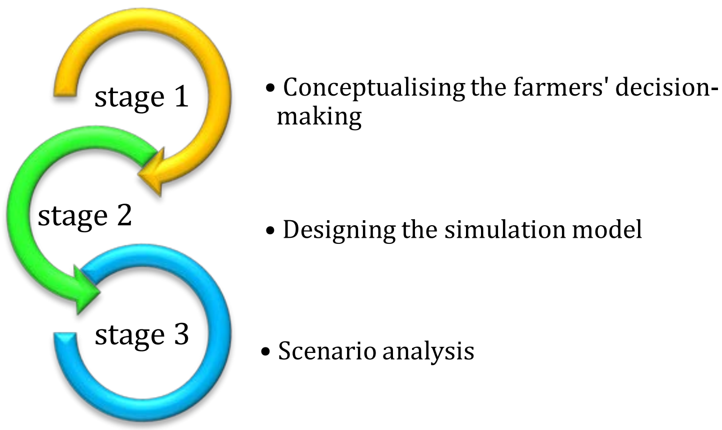


Figure 3-1 Research design

3.2 Research philosophy

The philosophical basis of this research is pragmatism. This approach is adopted for two reasons. First, it concentrates on problem-solving through the theory-practice nexus (Fellows & Liu 2015). Second, it is a flexible approach to accommodating multiple methods and techniques needed to understand phenomena and aid problem-solving (Creswell & Plano Clark 2011). Pragmatism satisfies philosophical concerns in the social and behavioural sciences by employing hypothetical testing (Patton 2005) and inductive processes (Neumann 2015). Further, the pragmatic approach fosters the practical freedom to choose the kinds of methods and techniques associated with qualitative and quantitative research approaches (Wheeldon & Ahlberg 2011; Creswell 2015) needed to build an agent-based model.

Pragmatism affords the researcher freedom: for collecting different sets of data (qualitative and quantitative data), for building virtual reality with a computer simulation, and for analysing scenarios to find answers for the research questions. It is an approach that is well suited to the development of an ABM. A pragmatic philosophical position allows for simulation modelling (e.g. spatial ABM) as a basis to test scenarios such as adoption of new alternative crops and irrigation expansion while simulating farmers' perceptions and considerations. In some disciplines and fields of work, using simulation may be seen as experimentalism but for this study the concept of scenarios was used because it is intrinsic to geo-design and very much a part of the interdisciplinary approaches used in planning to consider different land use options and the impact of change.

3.3 Mixed-method research

As stated above, a pragmatic approach provides a methodological setting that responds to the research questions and associated key concepts. Pragmatism allows for mixed methods

– critical to enabling the integration of qualitative and quantitative data and data analysis methods.

Mixed methods research has emerged as a ‘third’ methodological movement (Teddlie & Tashakkori 2009, p. 101) by connecting the existing traditions of quantitative and qualitative movements (Teddlie & Tashakkori 2009; Hall 2012). Mixed-method researchers reacted to the polarisation between quantitative and qualitative research by focusing on synthesis (Johnson et al., 2007) albeit there are different definitions for mixing qualitative-quantitative research methods. Creswell (2015, p. 2), for example, describes mixed method research

> an approach to research in social, behavioural, and health sciences in which the investigator gathers both quantitative (closed-ended) and qualitative(open-ended) data, integrates the two, and then draws interpretations based on the combined strengths of both sets of data to understand the research problem.

It could be argued that mixed method research balances the strengths and the weaknesses of both quantitative and qualitative research methods and gives the flexibility of mixing both of these methods (Amaratunga et al. 2002; Wheeldon & Ahlberg 2011).

The general aim of mixing qualitative and quantitative methods in this research was to allow the researcher to probe the complexity of farmers’ decisions on land and water in particular from the perspective of farmers who experience change such as new irrigation expansion in their region. This research utilises mixed method research for two reasons. First, the questions posed in this study about agricultural land use decision-making requires the identification of attributes from both qualitative and quantitative viewpoints. Second, the work of others cited above shows that the collective strength of both approaches (in this study interview and survey data) provides better insights into the research problems than each approach alone.

3.4 Multistage research design

Research design provides a structured process to integrate the methods and techniques based on and cognisant of a study's research philosophy. Research design is about the development of a smooth process to answer the research questions thereby helping to connect the research objectives to the data (Easterby-Smith, Thorpe & Jackson 2012). There are four basic mixed-method research design approaches: convergent design, explanatory sequential design, exploratory sequential design and embedded design. There are also advanced mixed method designs that go beyond the basic designs (Creswell & Plano Clark 2011) including intervention design, social justice design and multistage evaluation design (multiphase design) (Creswell 2015). This study has adopted multistage evaluation design.

Multistage design is a longitudinal design of different stages of a multilayer research project or program over time. A multistage mixed-method design was employed in this study to help design where and how to integrate different forms of data. Multistage design provides the flexibility needed in this research to address a set of interconnected research questions by offering 'an overall framework for conducting multiple iterative studies' over time (Creswell 2014, p. 101). Specifically, in this research, the design structure is such that the outputs and outcomes of one stage are expanded into other stages over time.

The value of multistage design is that it provides a coherent and structured way to build, create and study simulation and use of simulation scenarios. It reflects important characteristics of the framework developed by Steinitz (2012) and has been widely used by landscape architects and land use planners (Campagna & Di Cesare 2014; Steinitz 2014; Eikelboom & Janssen 2017). Geodesign is a way of bringing different stakeholders together through a constant design process by adopting a GIS platform, and applying different tools and techniques. As Steinitz (2012) has demonstrated, the geodesign framework is especially relevant and useful in the study of landscapes and land use change – where the agent and spatial data are integral to understanding what is happening now, what might happen and how socioeconomic and cultural factors might influence the biophysical and environmental factors.

The multistage research design of this study follows the geodesign structured iterations for exploring agricultural land use change under different scenarios such as irrigation expansion. Thus, this study is organised around geodesign methodology (iterative design framework) and implemented in its adaptation via Agent Analyst software, including Crop GIS-ABM. The nature of the objectives of this research required an advanced mixed-method design to enable qualitative and quantitative data collection and analysis across a three stage interconnected process. Understanding agricultural land use change through the 'iteration of connected quantitative and qualitative studies' (Creswell 2014, p. 100) is consistent with multiphase mixed-methods research design employed in the study.

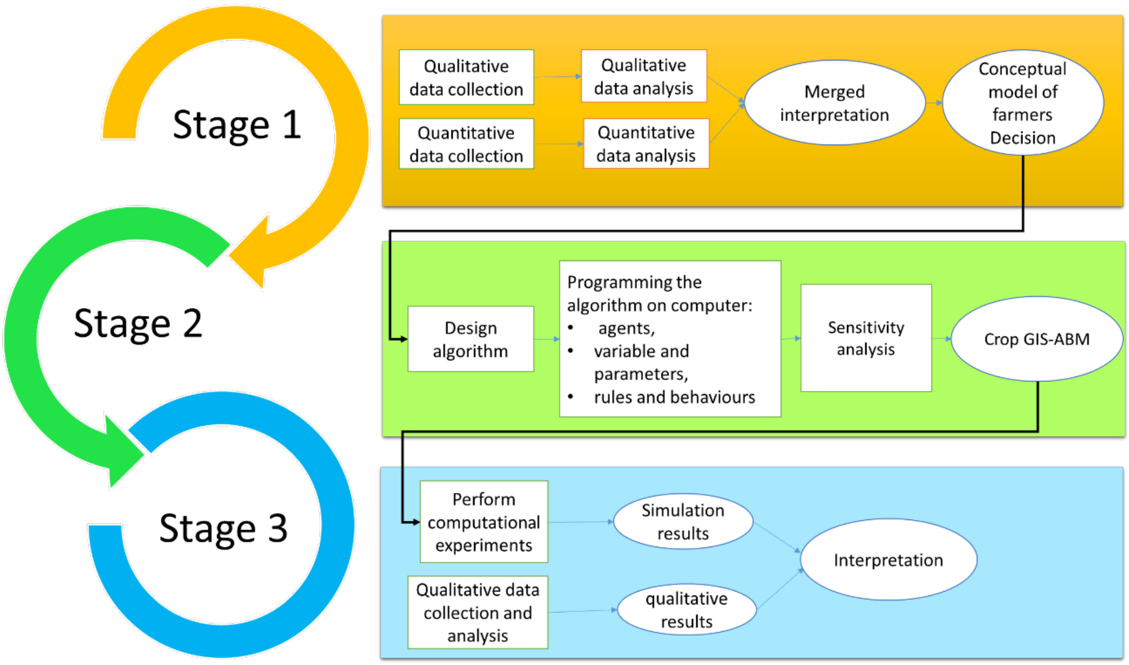


Figure 3-2 Multistage design of this research

Figure 3-2 outlines how the multistage research design that has been employed in this research. In this study, the complexity of the decision-making processes about land and water use required in-depth investigation of social, economic and environmental factors that affect farmers' decisions. This necessitated mixed methods to generate an appropriate mix of data. Multistage design, a structure, helped to explore the complexity of the farmers' decision-making processes through computational experiments under different agricultural scenarios.

Figure 3-2 shows this research as comprising three stages. In the first stage, both quantitative and qualitative data were collected and analysed as key inputs into a model to conceptualise farmers' decisions (i.e. agents). In the second stage, this conceptual modelling of farmers' decisions was converted into an algorithm and computer codes from which it was then possible to develop the simulation model. At this point the internal validity of the spatial ABM was checked. In the third stage, and intrinsic to multistage design, simulation experiments were conducted to explore and test agricultural scenarios under different experimental conditions. A further qualitative evaluative step involved the comparison of the simulation results with what was observed by the participants and by what they described via sketch maps. The following Sections (3.5, 3.6 and 3.7) elaborate more fully on the three steps adopted in the multistage design for this study and describe in some detail the specific methods used for each stage.

3.5 First stage: Conceptualising farmers' decision-making

The first stage of this research starts with the 'story of the stakeholders' (i.e. farmers) who live in the Dorset region and who are experiencing agricultural change through expansion of irrigation in their region. The purpose of the stage is to gain insights into how farmers decide on the adoption of irrigation and how this in turn may trigger or catalyse decision-making as to feasibility of new alternative crops. Within the first stage, grounded theory has shaped how the data was collected and analysed. Exploring factors that influence farmers' decisions involves considering different factors and thus needs different types of qualitative and quantitative data. Grounded theory is a suitable approach for this stage because it is a general method that provides systematic guidelines for gathering and analysing data to generate a conceptual classification (Charmaz & Belgrave 2007) and it is open to the emergence of meaning such as themes from data (Glaser & Holton 2005).

The conceptualisation of a farmers' decision model from the data systematically gathered through semi-structured interviews and a questionnaire is consistent with the grounded theory. Charmaz and Henwood (2008, p. 241) describe grounded theory as follow:

> . . . we gather data, compare them, remain open to all possible theoretical understandings of the data, and develop tentative interpretations about these data through our codes and nascent categories. Then we go back to the field and gather more data to check and refine our categories.

In the first stage of the research both qualitative and quantitative data were collected and analysed to discover patterns in interviews and observation data to capture participants' insights. This helped to clarify and explain the processes of decision-making on irrigation and crop types and their consequences.

3.5.1 Case study

The Dorset region in the North East of Tasmania was chosen as a case study for data collection. Figure 3-3 demonstrates the base map of the Dorset region in NE Tasmania as demarked by the pink boundary. The main industries in the Dorset region are agriculture, forestry and the fishing industry (Australian Bureau of Statistics 2017). The region has a population of around 7,200 people , and the average age is 48 (Australian Bureau of Statistics 2017). There are four main irrigation schemes in the region: Winnaleah, Great Forester, Upper Ringarooma, and Scottsdale (Tasmanian Irrigation (TI) n.d.).

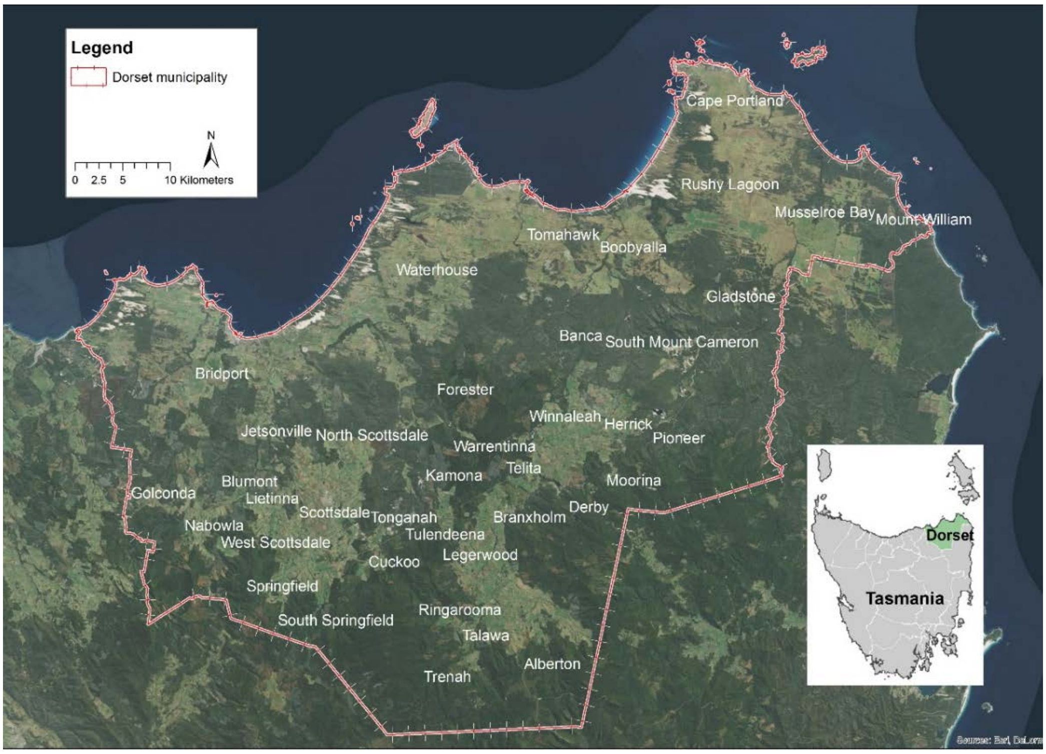


Figure 3-3 Dorset region basemap

The Dorset region was selected because it is a region experiencing change transitioning from traditional crops to higher value-added production as access to guaranteed water expands. There are also significant opportunities for the region to consider new alternative crops and value-added processing (Davey, Goodwin & Peterson 2013). Stakeholders in the region were interviewed to define what issues drive land and water use decisions. The researcher visited the Dorset region to observe the case study area and become more familiar with the characteristics of the region and its stakeholders. This involved visiting farms to observe and identify patterns in land use, collect land use information and categorise other land-based information.

Dorset region data, maps, and any other documents deemed essential to the study were collected from the open source datasets as well as governmental organisations and companies such as Irrigation Tasmania (with appropriate permissions). Other public documents were collected from various sources including the worldwide web and the LIST (Land Information System Tasmania) maps.

3.5.2 Qualitative data collection and analysis

Qualitative data was collected to understand the factors that influence farmers' decisions on land and water use. This phase consisted of semi-structured interviews with different stakeholders designed to understand in-depth the history of the region, plans, and schemes to scope the important, influential factors that affect farmers' choices.

Human Research Ethics Committee (Tasmania) Network granted 'Minimal Risk Ethics Application Approval' (Ethics Ref: H0015467) to this research project on 25 February 2016 (copy of the Ethics approval in Appendix A).

Semi-Structured Interviews: Semi-structured interviews were conducted because of the flexibility of open-ended questions, as noted by DiCicco-Bloom & Crabtree (2006). In the semi-structured interviews, the researcher asked some defined questions of participants allowing for further probing to explore topics and themes (as described in Appendix 2). Both the interviewee and interviewer were free to investigate further the emerging topics in the flow of dialogue, during what might also be termed a facilitated conversation. Interviews took place face-to-face in the Dorset region or in Launceston (the major urban area closest to the Dorset region), whichever was more convenient to each interviewee, and were recorded using the MP3 Recorder device.

The aim of interviewing the stakeholders was to capture the voice of participants and their experiences of living and practising agriculture in the Dorset region. A snowballing 'sampling' technique (Byrne 2001; Streeton, Cooke & Campbell 2004; Noy 2008) was used to find potential respondents based on the recommendation of other participants. This technique was useful because the Dorset stakeholders recommended other potential participants who not only had valuable knowledge but also were interested in participating in this study.

Despite the usefulness of snowballing technique as sampling method in qualitative research, there is a risk for sample's diversity (Kirchherr & Charles 2018). To decrease the risk of snowballing technique, firstly, a few potential participants who have community knowledge were interviewed and asked to recommend others with the variaty of interest, skill, and knowledge of farming, irrigation and the Dorset region. Therefore, a variety of stakeholders recommended by participants through snowballing technique such as farmers, some experts from Tasmanian Irrigation, Dorset Council staff, local food processors and Natural Resource Management (NRM) staff, and DPIPWE.

The Participants: A total number of 20 people were approached. The number of participants in this study was determined based on the literature where 15 participants, ± 10 is appropriate for PhD qualitative research (Mason, 2010). Marshall et al. (2013) have observed eighty-three qualitative studies in leading International Science (IS) journals and recommend that 15 to 30 participants could provide rich and detailed data for a qualitative study. Creswell et al. (2007) recommended that +10 interviewees in grounded theory studies are sufficient. Given that the intent of the stakeholder interviews was to gain insight into factors that influence decision-making and to use these factors as the first level of input into the development of a simulation model, this was an appropriate approach. It is acknowledged that as the simulation is further refined in subsequent research these factors and methods to obtain them may be similarly refined.

Nineteen stakeholders participated in this study. Some participants suggested others who were potentially interested or in their view had an under-represented voice. Stakeholders including farmers, local food processors and community members, experts from Tasmanian Irrigation (TI), Dorset Council staff, local food processors, Natural Resource Management

(NRM) staff, and DPIPWE staff were interviewed. Each participant was chosen because they play unique roles and brought different perspectives on land and water use and because they had the capacity to answer the various components of the research questions.

Interview questions were open-ended. Some general questions were asked to cover different participants' experiences, and some narrow questions were asked to help participants focus on agricultural aspects, time, and location in the Dorset region.

Interview Data Analysis: Interviews were recorded electronically, and the data was transcribed verbatim into a meaningfully-consistent written form of information. The transcripts were checked against the recordings multiple times by the researcher to ensure they accurately reflected the information given by respondents, as recommended by Braun and Clarke (2006). The researcher spent time becoming familiar with the data and checked the transcripts with the original audio recordings to ensure the transcripts are accurate. Although the process was time-consuming, it helped the understanding of the data and facilitated analysis and interpretation.

The interviews transcripts were then imported into NVivo 11 software (QSR International n.d.). NVivo is a data analysis software that supports qualitative and mixed-method research by facilitating thematic coding of the interview data. Thematic analysis is described by Braun and Clarke (2006, p. 6) as 'a method for identifying, analysing, and reporting patterns (themes) within data'. In this study a thematic analysis method was employed to construct meaningful themes from participants' opinions. The step-by-step thematic analysis for investigation of major themes was as follows:

- The researcher's repeated reading of transcripts to build familiarity with interview data, making a note and defining possible codes in NVivo.
- Initial codes were generated from transcription, and the data were organised into meaningful groups, as noted by Tuckett (2005).

- The researcher searched for themes by connecting the codes and re-focusing on the broader level of themes.
- The preliminary themes were reviewed to ensure the themes were coherent.
- Each theme was named and clearly defined to ensure the research questions could be answered through the themes.
- The results of the analysis were extracted with some examples from transcripts to show the findings.

The results from the above are presented in Chapter Four.

3.5.3 Quantitative data collection and analysis

After the interviews, participants were given the option of also completing a questionnaire. The same questionnaire was provided for all groups of stakeholders.

Questionnaire: A questionnaire was included for two reasons. Firstly, for the purpose of triangulation where the results from both sources of evidence (interview and questionnaire) could be tested for reliability and validity of findings. Triangulation of evidence collected from multiple sources is considered to be more robust and compelling (Yin 2003). The result of questionnaire was triangulated with the interview finding as well as available literature on farmers' decision-making such as Macquarie Franklin report (2013). Secondly, a questionnaire extended the data gained from the interviews. The questionnaire (Appendix 3) consisted of thirteen questions including multiple-choice questions, open-ended questions, and one spatial question (specifically, participants were asked to sketch on the map). All the participants who were interviewed agreed to complete the questionnaire as well.

Questionnaire data analysis: The questions in the questionnaire were categorised into three sections to support the triangulation of interview data and help with further analysis of the emerging themes which were:

- The possibilities for the future of the Dorset region
- Alternative crops/livestock for the region
- The main influential factors that affect farmers' choices to grow alternative crops/livestock in the Dorset region

The analysis of the quantitative questionnaire data was undertaken using Microsoft Office Excel software. In particular, descriptive statistics were generated from the questionnaire survey data, including scale means, item means, standard deviations percentage and frequencies of responses. NVivo software was used for content analysis of the written responses to the open-ended questions in the questionnaire survey. Codes based on themes and patterns were identified within the responses for content analysis. As Maxfield and Babbie (2014, p. 36) describe, 'coding is a process whereby raw data are transformed into a standardised form suitable for machine processing and analysis'. The codes that represent terms and phrases in written responses were elicited. Themes were identified through multiple readings of questionnaire survey responses and rigorous categorising of the codes. Quantitative analysis allowed conclusions to be drawn about different alternative crops/livestock scenarios for the future of the Dorset region.

3.5.4 Integration and interpretation (Qual + Quant)

As outlined earlier, the aim of stage one was to understand stakeholders' perspectives on the future of the region, irrigation expansion, alternative crops/livestock and value-added processing. Grounded theory was used to generate conceptualisations of farmers' decisions drawn from these data. The outcome of each 'Procedure' is called the 'Product' and Figure 3-4 demonstrates the 'Procedure' and the 'Product' of each method:

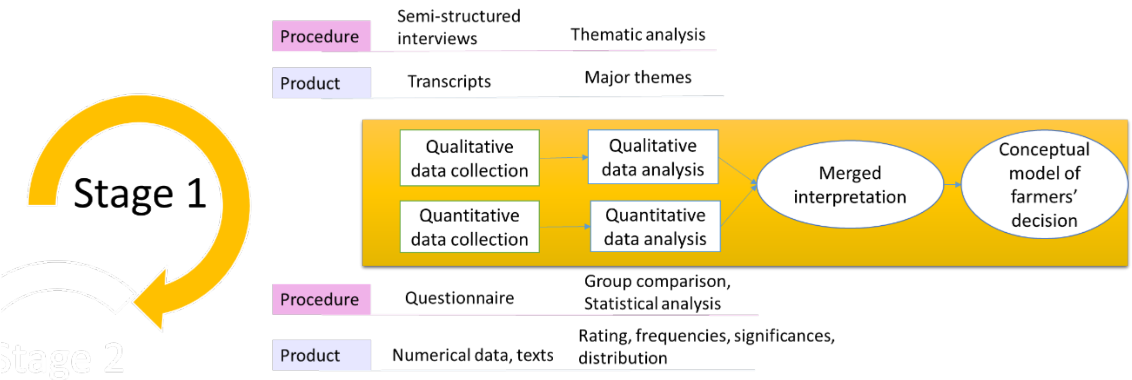


Figure 3-4 Research design for conceptualising the farmers' decision model in stage 1

The results of two different data sets are merged to compare the findings. The results were then examined to confirm the validity of qualitative results by cross reference to quantitative results. The interpretation was drawn from the two databases, and the conceptual model of farmers' decisions subsequently developed. The farmers' decision model was then conceptualised based on the major themes, and a conceptual model was the end-product of this stage of the research process. A conceptual model of farmers' decision-making is a set of concepts and decision factors that represents the relationships and processes among system components. Robinson (2008) defines a conceptual model as 'a non-software specific description of the computer simulation model' which provide a basis for clarifying the process of simulation model development and use. As it will be demonstrated in Chapter Four, multiple biophysical, social and economic factors were identified as having influenced farmers' decision on crop choice.

3.6 Second stage: Designing the simulation model

In the second stage, algorithms of the spatial ABM are developed. A key input is the conceptual model of factors that shape farmers' decision-making processes derived from the first stage. Agents are defined, the agent's behaviours and rules are formalised, and variables and parameters initialised in the computer simulation. The complex reality of the farmers' decision-making process is programmed to allow for the simulation of a range of possible futures.

3.6.1 Simulation

Stage 1 data collection yields multiple biophysical, social and economic factors that affect farmers' decisions on crop choice. The data demonstrates that the farmers' decision model is complex, and their relationship to the farm land and their interaction with other farmers is a non-linear process. This being the case, it is difficult or almost impossible to answer the research questions of this study by analytical reasoning alone. As was revealed in Chapter Two, a more promising way to tackle the complexity and non-linearity of the farmers' decision model is through simulation. Simulation is a robust research method (Dooley 2002; Grüne-Yanoff & Weirich 2010; Tolk et al. 2013) employed to spatially and statistically analyse quantitative data and test out scenarios in a 'virtual laboratory'.

Axelrod (2006, p. 97) describes simulation as 'a third way of doing science in contrast to both induction and deduction'. Simulation as a new methodology sits between theory and experiment (Winsberg 2003). The simulation starts with a set of assumptions (deductive method), then uses an experimental method based on computer-based rules instead of direct analytical analysis for generating the simulated data to find patterns (inductive method) and discovers the consequences of assumptions (Axelrod 1997; Gilbert & Troitzsch 2005).

The structure of simulation for this research consists of the following steps:

- Design algorithms for spatial ABM based on the conceptual model of farmers' decisions;
- Program the algorithms by:
    - Defining the agents and their farm lands,
    - Formalising the farmers' actions and behaviour, and

- o Initialising variables and parameters;

- Execute the spatial ABM to check the internal validity and usability of the simulation model.

Figure 3-5 shows the research design for transferring the conceptual model to a computational simulation model:

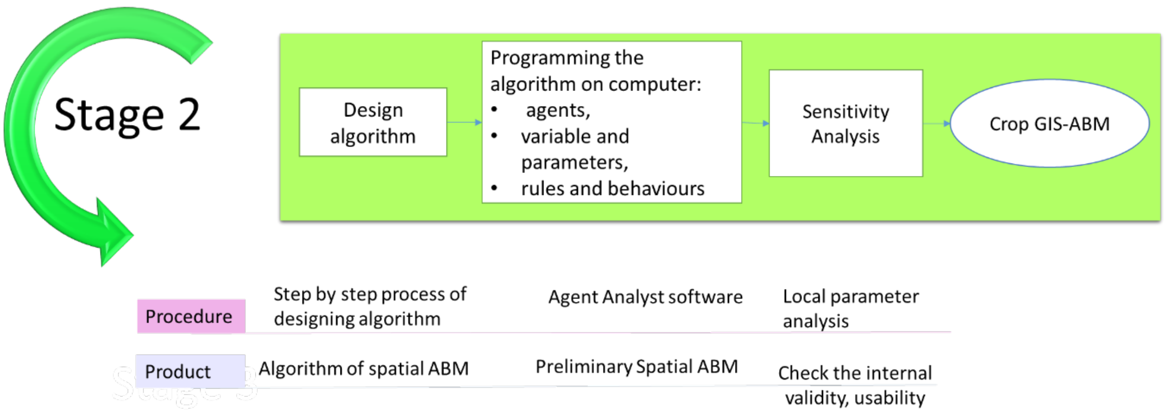


Figure 3-5 Research design for programming the spatial ABM (stage 2)

Spatial Data: For this stage of the research, the GIS layers (vector and raster layers) of land parcels, crop suitability, land capability, and irrigation served as the main sources of spatial data. The spatial data is representative of the Dorset region land and water resources, and was gathered from different sources including the DPIPWE, Tasmanian Irrigation Ltd, and the Land Information System Tasmania (LIST) website. The numerical data about the gross margin of different crops were sourced from DPIPWE.

Spatial ABM: The instrument that was used in this stage was Agent Analyst software that adequately represents and accommodates both the complex spatial structures in GIS and the rich dynamical processes of ABM. Part of the complexity and contribution of this research methodology is the ways in which this researcher undertook the following tasks:

- linked the ABM data and GIS data using Agent Analyst software,

- developed algorithms drawing on the structures with Agent Analyst software based on the farmers' decision model (section 3.5),
- tested the simulation model (called Crop GIS-ABM).

After data were coded in the computer programme (Agent Analyst software) following development of the algorithms, several trial experiments with a set of random parameters were executed to check the internal validity and usability of the spatial ABM. Then after checking to what extent and under what conditions the simulation mimicked the farmers' behaviours, the spatial ABM could be used to reliably perform the experiments and analyse the agricultural scenarios. The key feature of Stage Two lies in the design and development of the algorithm and the construction of a simulation model in Agent Analyst software by the researcher. The simulation model, called Crop GIS-ABM, is explained fully in Chapter Five.

Analysis of the simulated data: The analysis of simulated data was undertaken using sensitivity analysis to assess the reliability of emergent new patterns and quantify the variability in the computational experiment outcomes from model parameters. Richiardi et al. (2006, p. 21) describe the sensitivity analysis as a collection of tools and methods used for investigating how sensitive the output values of a model are to changes in the input values'.

A sensitivity analysis was conducted by perturbing each parameter by ±10% individually, re-running the model, and examining changes in simulated outcomes. Sensitive parameters were defined as those causing substantial variation in simulated land use based on the said parameter perturbation. The simulation was performed with an experimentally modified parameter (by ±10%), and the robustness of the simulation outcome regarding the choice of parameters was examined. By simulating variations in a specific factor of the spatial ABM, the changes in the emergent crop patterns can be revealed, and the sensitivity can be measured (Helbing & Balietti 2011). Sensitivity analysis of the simulated crop patterns was conducted using a local 'one-at-a-time' approach (O'Sullivan & Perry 2013) where all parameters were kept constant except one parameter of interest which was varied. The sensitivity analysis helped test how well the crop patterns (land use) were reproduced in the ‘virtual laboratory’.

3.7 Third stage: Scenario analysis

In the third stage of the research design, agricultural scenarios were defined, and the spatial ABM was executed in multiple times to simulate the effects of different agricultural scenarios. Using ABM and GIS, the simulation was set up as a ‘virtual laboratory’ allowing for different computational experiments and investigations of complex land use change based on farmers’ decisions. Agricultural scenarios under different experimental conditions were tested and the results of the simulations visualised in ArcGIS as maps. The simulated maps and the participants’ sketch maps were also compared as a further ‘test’ of the simulation results. The interpretation of the results of both methods provided further insights into the legitimacy of simulated data.

3.7.1 Simulating agricultural scenarios

The focus of Stage Three is on testing scenarios under different experimental conditions in spatial ABM. The spatial ABM simulates farmers’ behaviours and interactions under different agricultural scenarios to investigate individual farmer decisions about their own land and crop types (micro-scale decisions) as well as to understand how this influences macro-scale regional land use patterns.

To achieve this, a scenario of the farmers’ decisions was first defined. Different experimental conditions were formalised, and the parameters initialised in the simulation model. Farmer agents’ decisions were simulated, and their behaviour and interactions under different experimental conditions were tested, and the regional crop pattern visualised in the

GIS display. The plausibility of the scenario was examined by how well the expected range of land use pattern emerged from the farmer agents' decisions and interactions.

Computational experiments: The spatial ABM designed in the second stage (called Crop ABM-GIS) is a type of agent-based simulation. An ABM is a computer-generated model that enables systematic experiments to be conducted and repeated for the exploration of human-environmental interactions (Parker, DC et al. 2002; Gilbert & Troitzsch 2005; Groff 2007). The simulation enables scenario testing when empirical research experiments are not ethically feasible or too costly (Heckbert 2010). For example, it is impossible to test the effect of an agricultural policy on farmers' decisions in a field trial, or the analysis of the emergence of possible agricultural land use patterns under an irrigation expansion scenario over the next ten years. It is too difficult and time consuming without the use of simulation and tools such as spatial ABM.

Therefore, farmers' decisions were simulated to demonstrate how plausible scenarios would address sets of questions often asked of agricultural land use in land use decision-making. Farmer agents represent farmers who decide on the crop types under different experimental conditions. In this way, agents' optimisation behaviours and random behaviours can be changed under different experimental conditions. Thus, different scenarios can be tested in controlled decision-making settings to study the consequence of farmers' decisions on land use patterns.

3.7.2 Qualitative spatial data collection and analysis

The integration, visualisation and analysis of qualitative spatial data with GIS are referred to as Qualitative Geographic Information Systems (Boschmann & Cubbon 2014). Analysing qualitative spatial data such as sketch maps with GIS allows participants' spatial experiences and knowledge to be understood (Jung & Elwood 2010). In this study, these kinds of stakeholder spatial insights and experiences were investigated to facilitate additional interpretation of simulated data and provide further in-depth spatial information on agricultural land use changes such as occurs under irrigation. At the end of the semi-structured interview, participants were asked to identify where in the region farmers might be interested in investing in irrigation or new alternative crops. These identifications were executed as sketch maps.

Sketch map: A sketch map is a qualitative method that assembles participants' spatial narratives and experiences (Boschmann & Cubbon 2014). Asking participants to sketch on maps not only improves the conversation during an interview but also enriches the quality of specific spatial data collection (Son 2005). In this study, the participants drew sketches, based on their insights and spatial experiences, on spatially referenced maps of the Dorset region. The participants sketched out the areas that farmers might produce hemp by expansion of irrigation in the Dorset region. This data was collected and integrated into the GIS for analysing and visualisation.

Sketch maps analysis: The sketch maps were digitally scanned as image files. The image files were imported into the GIS and georeferenced with Dorset's existing shapefile[2]. All marker features (districts/areas) from the sketch maps were manually transferred into a polygon (vector typology in GIS). The digitised sketch maps and their features were compared for common overlaps among polygons. The high overlap areas demonstrate the areas that farmers might tend to invest in irrigation and adopt new alternative crops based on the participants' insights.

Finally, as Figure 3-6 illustrates, the simulation data and qualitative GIS data were merged, and the results interpreted:

[2]GIS shapefile is a vector layer that stores data and attributes of geographic feature in the ArcGIS ESRI software.

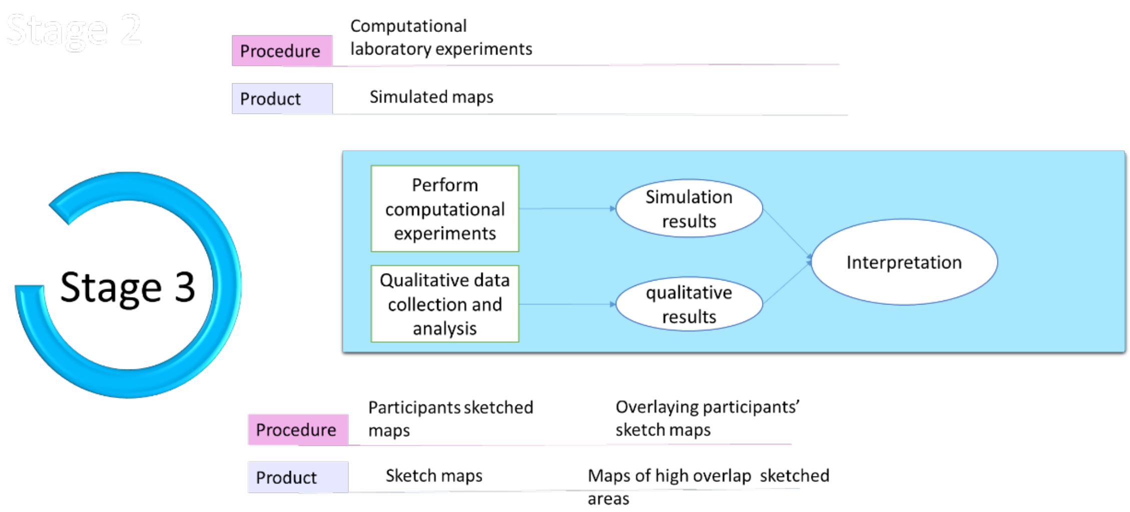


Figure 3-6 Research design for analysing the agricultural scenarios (stage 3)

3.8 Synthesis using multistage design

This research uses mixed methods. It does so as a means of identifying critical input data for a conceptual model of farmers' decisions as agents, which when integrated with GIS form a platform for a spatial ABM or ABM-GIS. The qualitative data provides additional insights on farmers' future casting which can be used as a form of merged interpretation with a range of simulations developed under experimental conditions. The development and scenario testing of this kind of ABM-GIS was undertaken using a multistage approach. The multistage approach is described in Figure 3-7.

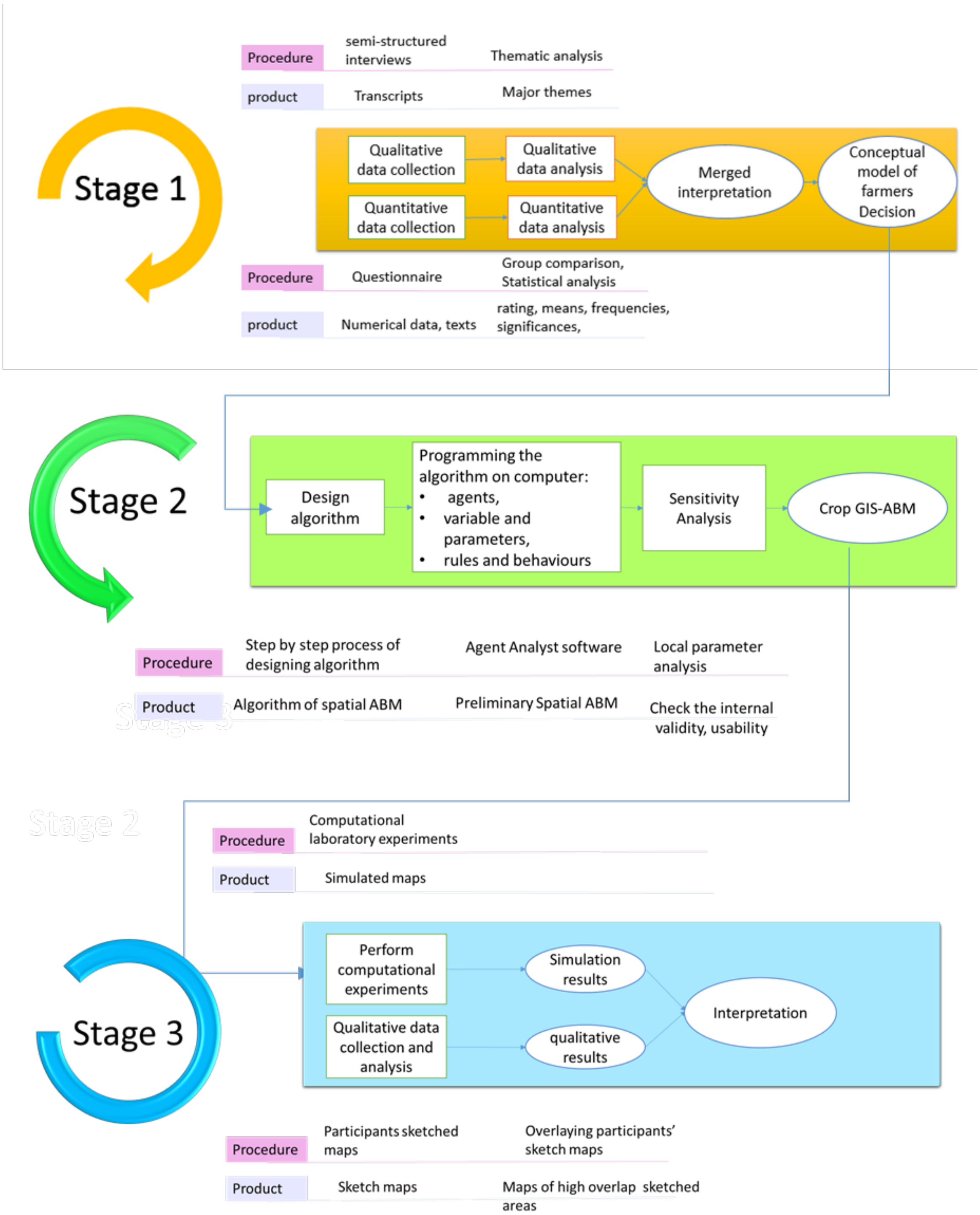


Figure 3-7 Multistage mixed method research, procedures and products

Table 3-1 outlines how the methodology enables the research questions to be addressed.

Table 3-1 The relationship between Research Questions, and multistage evaluation design and methods

Research Question (RQ)	**Stage 1: Building a conceptual model of farmers decision making**	**Stage 2: Designing the simulation model**	**Stage 3: Analysing agricultural scenarios**
What economic, social and environmental factors influence farmers' decisions on crop choice and what are their relative impacts?	Semi-structured interview Questionnaire Thematic analysis Group comparison, statistical analysis		
What kind of simulation model is required for the integration of qualitative and quantitative data with ABM in a GIS-based computational 'virtual laboratory'?		Step by step process of designing algorithm Agent Analyst software Sensitivity analysis	
Could farmers' decisions and behaviours on adoption of new alternative crops be simulated to answer: To what extent does the irrigation expansion promote the diffusion of alternative crops in the region? How does farmers' crop choice alter the regional land use and the crop patterns over time?			Computational experiments Participants' sketched map Overlaying sketch map
Could agricultural land use planning in Australia benefit from a decision support simulation model, and in what ways could a simulation model be useful?	Interpretation of the results of three stages		

Chapter 4: Building a conceptual model of farmers' decision making (Stage 1)

4.1 Overview

This Chapter presents stage one of the multistage design of this research. Stage one outlines how the farmers' decision model was conceptualised. A key aim of this research is to integrate farmers as the agents of micro-level decisions into a spatial ABM. To do this requires an understanding of the factors that influence and frame farmers' decisions. It is argued that this is important but as the review of land use planning in Chapter Two revealed, is often missing in rural land use and agricultural planning. However, cumulatively these decisions shape land use and water utilisation. Specifically, the overall aim of the first stage is to explore how different stakeholders perceive and make sense of introducing irrigation expansion and new alternative crops/livestock in socioeconomic and agricultural contexts, and in so doing provides insights that address the first research question:

- *(Q1)- What economic, social and environmental factors influence farmers' decisions on crop choice and what are their relative impacts?*

In this Chapter, qualitative and quantitative data are analysed to provide insights into factors that influence farmers' decisions in regards to their land and more particularly on the adoption of innovation or change such as irrigation and new alternative crops (first stage).

Identifying the key decision factors helps to better design a conceptual model of farmers' decision-making process. The complex decision-making process is investigated from the perspective of people who experience the agricultural changes in the region. While it is broadly understood that farmers make decisions that relate to biophysical characteristics there are also social, cultural, economic and environmental factors at work (Boully et al. 2005). However, for Stage 1, the concern is to identify key factors as a starting point and input for simulation. Development of the simulation model and testing of scenarios may subsequently reveal additional factors that shape farmers' decision-making.

The process starts with clarifying the problem, gathering information about the study area and identifying the key stakeholders, in order to conduct surveys and interviews in the Dorset region. As discussed in Chapter Three, the qualitative data was collected by conducting semi-structured interviews, and quantitative data was gathered by surveying the participants. Thematic analysis was employed to analyse the qualitative data, while the questionnaire data were analysed statistically. The results of both analyses were then merged and interpreted to develop a conceptualisation of a farmers' decision model around irrigation expansion and alternative crops/livestock.

4.2 Profiles of participants

As described in Chapter Three, while a total number of 20 people were approached, 19 people participated in the study, which is more than 95% response rate. As noted in Chapter Three, the number of 19 participants in this study was verified as appropriate for the study and a snowballing sampling technique adopted to find potential respondents to participate in the study. Different stakeholders such as farmers, some experts from Tasmanian Irrigation, Dorset Council staff, local food processors and Natural Resource Management (NRM) staff, and DPIPWE were interviewed. These different categories of people and stakeholders were recruited to provide insights into agricultural land use issues from the perspectives of the various stakeholders and to identify their perspectives on irrigation expansion and alternative crops/livestock.

<u>Demographic profiles of participants</u>

The age of the stakeholders who participated in this study varied. Participants were classed into seven age groups from 36 to 71 years. As the Figure 4-1 illustrates the breakdown of participants' ages is as follows: two participants were younger than 40 years of age, eight participants were aged between 41 and 60; and nine participants were aged between 61 and 75 years of age. The average age of people in the Dorset region is 48 (Australian Bureau of Statistics 2017). Within the sample, the average age for participants was 60, indicating most of the participants in the study were older than the average age of the general population.

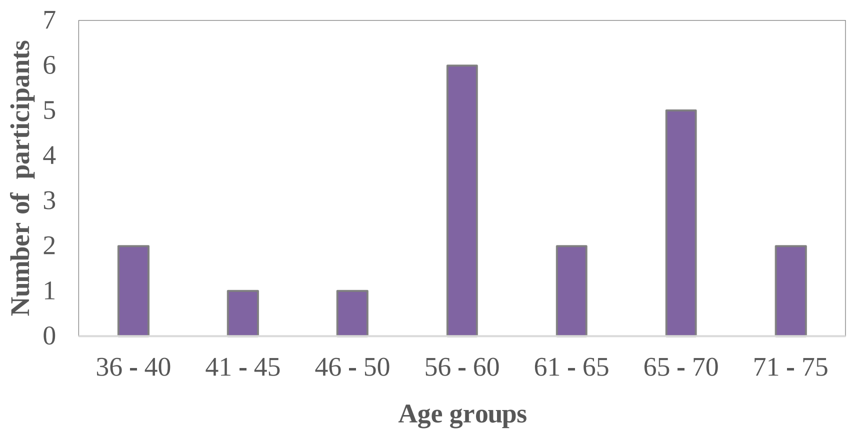


Figure 4-1 Participant age groups

The profession of the participants is presented in Figure 4-2, showing that 58% of the participants were practising farmers and the majority of the farmers (80%) had more than 21-25 years of experience in farming. Others who participated in this study were not practising farmers, but they were involved in jobs and fields related to agriculture, some in high managerial positions and influential roles as community members.

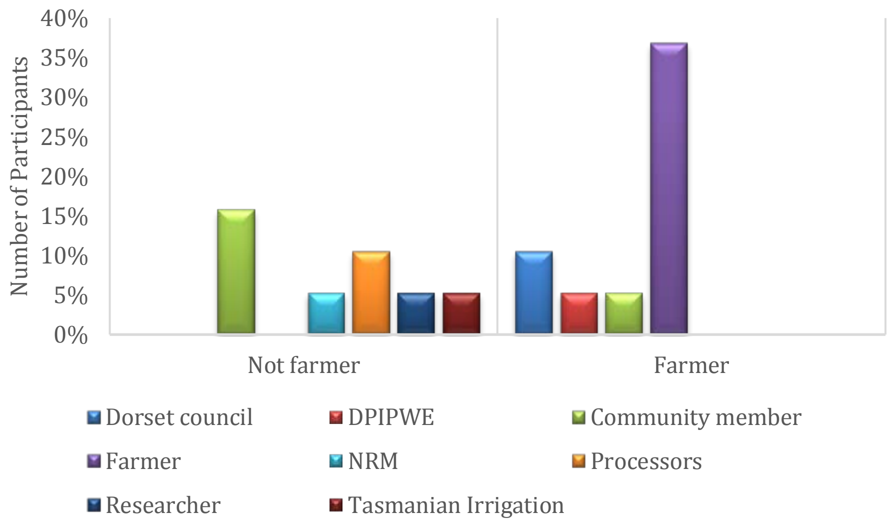


Figure 4-2 Professional affiliation of participants to agriculture

These demographic profiles show that the participants were well varied across stakeholders. Some were experienced in the agriculture sector, and/or played a key influential role in the Dorset community. Although the questionnaire data were not representative of stakeholder groupings, the survey data along with the interview data does provide insights into agricultural land use change and contributes to the reliability and validity of the research outcomes.

4.3 Thematic analysis of interview data

Thematic analysis (Braun & Clarke 2006) was employed to analyse the interview data as the means of conceptualising and understanding the stakeholders' experience and insights on agricultural land and water use in the region. The interview data were analysed for the key themes through six steps of thematic analysis (Braun & Clarke 2006) and as discussed earlier in Chapter Three, NVivo software (QSR International n.d.) was employed to facilitate the process of thematic analysis.

After the interview data were organised in NVivo software, the main ideas were elicited, terms and phrases in interview responses were coded from the transcription, and the initial codes were organised into meaningful groups. Further, the characteristics of the research questions were reviewed, and research questions were transformed into phrases to represent the information in the data (focus prompt). Table 4-1 illustrates these characteristics extracted from the research questions for the thematic analysis.

Table 4-1 Major codes for thematic analysis

Major code/nodes	**Sub-codes**
Economic aspects	The market price of crops, milk price, the economic issues, size of the farm
Social aspect	Neighbours' decisions
Environmental aspects	Land capability, the soil, slope
Irrigation expansion	Availability of irrigation, the area for irrigation expansion, availability of three phase electrical power, critical issues for investment
Region's characteristics and issues	
Alternative crops/livestock	
Alternative value-add processing	

The codes were defined based on the questions, transferred into phrases in the NVivo software and assigned to the relevant data that represent similar information in the transcripts. The relevant information was identified and put into main nodes. New sub-codes (child-nodes) were created to contain new information related to the research questions. Figure 4-3 shows a snapshot of the nodes and sub-codes in NVivo software.

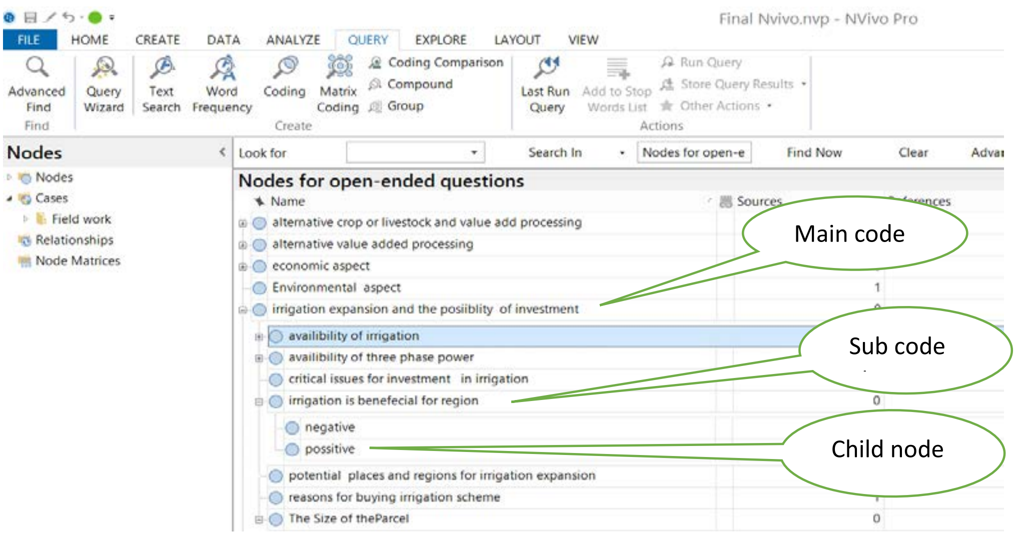


Figure 4-3 Snapshot of main codes, sub-codes and child-nodes in NVivo software

Sub-themes were grouped into broad themes. NVivo software allows combining of different codes and drawing mind-maps. The mind-maps helped to better understand the connection between the codes and the emergence of the themes.

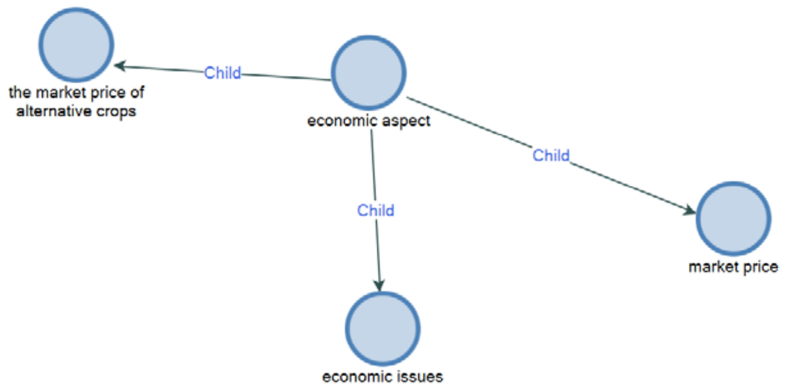


Figure 4-4 Mind-map of the theme (e.g. economic aspect) with codes

The preliminary themes were reviewed to ensure they were coherent. All the codes extracted for each theme were reviewed to check whether consistent patterns were apparent or not. The theme was then checked to test whether they were accurate in relation to the whole interview data. As suggested by Braun and Clarke (2006), each theme was defined concisely to ensure that the scope and content of each theme were sufficient to answer the research questions. The themes were analysed and the results recorded with examples from transcripts to support the findings, show evidence in the report, and decrease the complexity of the interpretation.

4.3.1 Emergent themes on farmers' decision making

The process of locating and listening to the range of participants' voices, transcription, and importing to the NVivo software allowed the researcher to identify participants' insights as themes and enabled the possibility of linking these insights back to the research questions.

Eight themes were extracted from participants' insights as the most important factors affecting farmers' decisions to invest in irrigation and produce alternative crops/livestock, namely:

- Positive futures for agriculture in the Dorset region
- The characteristics of the farmland
- The profitability and market price of alternative crops/livestock as a decision factor
- Irrigation availability as a decision factor
- Neighbour's decision as a decision factor for investing in irrigation, alternative crops/livestock
- The availability of three-phase power as a decision factor
- The accessibility of value-add processing plants within a reasonable distance as a decision factor
- Possible alternative crops/livestock (e.g. hemp) with the potential to attract farmers' investment in irrigation

It was relevant to examine these themes more closely. Where appropriate this included farmers' own words and expressions, with no correction of any obvious grammatical errors. Participants were identified only by a code representing their sequential inclusion in the research process.

Theme 1: Positive futures for agriculture in the Dorset region

Tasmania's economic strengths and subsequently the Dorset region's potential lies in natural assets including the rich soil types and reliable rainfall, and a pleasant climate for agricultural expansion (Hennessy et al. 2008). Based on the interview findings, it was found that the farmers' and other stakeholders' insights into the future of agriculture in the Dorset region is positive. Participants felt that the agricultural sector would grow in the future enabled by changing the current farming practices, and with the expansion of irrigation providing security and reliability for the farmers. In describing how positive and promising the future of agriculture is, participant A121 stated:

> It would be my understanding and belief that the future for agriculture in Dorset forward, is extremely promising. It's a function of the quality of the soil. Quality of air. Quality of rainfall, generically that makes it possible to grow virtually any cool climate agriculture crop. I would think really very positive.

From the participants' perspective, the expansion of irrigation also plays a significant role in the future of agriculture. Participant A106 expressed a positive future for the region because of Dorset's natural resources and the expansion of irrigation:

> There's certainly a lot of potential in the region. We've got good soils. We've got a really good climate, have reasonably reliable rainfall. We're in the process of nailing down another irrigation scheme which will be the third for the district . . . It certainly gives us security and reliability.

These findings suggest that there is potential for agriculture to grow in the Dorset region with the expansion of new irrigation schemes.

Theme 2: Characteristics of the land

The analysis of interview data revealed that biophysical characteristics of the land (e.g. soil depth, slope, size, texture) are important factors in farmers' decision-making process. Most of the participants mentioned that soil in the Dorset region is fertile, affording considerable potential for growing alternative crops/livestock through irrigation expansion. Furthermore, the biophysical characteristics of the farms (e.g. land capability, soil, the slope, drainage) are the main factors influencing farmers' decision on growing the crops/livestock. As all of the participants mentioned, one of the critical considerations for investing in an irrigation scheme is the land capability and crop suitability of the farmland. All of the participants mentioned an interest in adopting irrigation when positive about the economic return. As participant A106 summarised:

> In terms of land, capability limits on the sort of crops you can grow, once you get beyond that red soil area.

Eleven participants also mentioned the size of the farm playing a role in farmers' decision-making because small-scale farms inhibit farmer investment in irrigation and buying 'big' irrigators. This was assumed by participant A115, who stated:

> The size of the farm certainly dictates what's affordable. Small farms are very difficult to make profitable.

Other non-farmer stakeholders (e.g. participant A120) noted that the size of the farm is relevant to the marginal gross enterprise and deters farmers from buying into an irrigation scheme:

> Possibly because of the scale of it. If you're running a little farm, you're not going to have that extra cash to invest.

While more than half of the participants mentioned that the size of the farm is a deciding factor, others said that the size of the farm is not a key factor for decision-making on irrigation and crop types. Rather, they emphasised other factors such as the farmer's personality and attitude to taking risks, and soil type. Intensive farm systems can affect small farm holders' decisions whether to buy into an irrigation scheme and add value to their farm. For example, interviewee A106 stated:

> I think if you look across the water sales that have been achieved in this irrigation scheme – and a lot of it comes down to land capability, obviously – you can make a fair bit of money out of a small area of land if you want to do it intensively enough.

Although there are differences between the farmers' insights about the size of the farm, not surprisingly all participants agreed on the land capability and the biophysical constraints as major deciding factors. The biophysical characterisation of the farmland is the most important factor that determines the profitability of the farm enterprise and one of the influencing decision factors.

Theme 3: Profitability and market price of alternative crops/livestock as a decision factor

The market drives the price of the agricultural product, and it is taken as a response to the demand for crops/livestock (Tomek & Kaiser 2014). Investments in new alternative crops/livestock are riskier than traditional crops/livestock with known expenditure. The participants were asked about the most important economic factors that affect their decision-making in regards to alternative crops/livestock in the Dorset region.

Responses suggested that the market demand for agricultural crops/livestock is most often the initial motivation to adopt irrigation or a new type of crop and farming system. However, the diffusion of innovation literature suggests that farmers usually do not adopt a new farming system at the same time as the opportunities appear on the market (Diederen et al. 2003; Doss 2006). Rather, farmers analyse their resources (land, water, machinery, etc.) and, if the new crop or land use prospect returns them equal or better than the current products, then they are more likely to decide to grow an alternative crops/livestock. As participant A110 stated:

> The drivers of change on farms, whether it be to adopt irrigation, or whether it's to have a new type of crop, or a new pasture animal system, or something, that's driven by dollars . . .

Analysis of the interview data supports this view. Farmers invest in a new product if the crops/livestock is genuinely high value by the time farmers get to market. Moreover, farmers are more likely to invest in new technologies such as irrigation when they can ensure the price differentiation and profitability of the products that they are delivering to markets. Participant A108 summarised this by saying:

> There's only one thing that will influence the farmer. They want to put [on] water to make money. It's that simple.

As evidenced by the experience of the participants, economic factors and market price of the crops play integral roles in decision-making on growing alternative crops/livestock. The profitability of the farm products upon delivery to markets (the price differentiation) is identified as a critical or important economic factor for deciding on producing alternative crops/livestock. Not surprisingly, other economic factors such as irrigation and transport costs are also noted by the respondents as factors that affect farmers' decisions. Thus, the interview findings supported the view that farmers make decisions based on return on investment and the gross margin of agricultural products.

<u>Theme 4: Irrigation availability as a decision factor</u>

The oldest irrigation scheme in the Dorset region is called the Winnaleah Irrigation scheme. Other irrigation for use in agriculture are the Upper Ringarooma, Great Forester and the proposed Scottsdale irrigation districts. Most participants mentioned that irrigation is one of the essential factors for deciding on alternative crops/livestock and emphasised access to irrigation as an important factor for growing crops. Participant A107 stated:

> Most definitely. Most definitely. It is one of the most beneficial things to farming expansion, whether it be dairy, beef, or cropping. It doesn't matter what sort of cropping. You still got to use water . . . but with the expansion that's coming through, that will all be pressurised . . . That [irrigation] is one of the most significant things for this area will be that water allocation and the water that's coming on stream.

Expanding on this point another participant (A116) noted:

> . . . if any poppy farmers crop's going to fail, it'll be the dry land farmers, because they'll get something, but they're just dreadful those crops that haven't got irrigation.. . . It's so

> frustrating because they [farmer] could have put a little bit of water, just a little bit of water on, would have doubled their [crops].

Participants also mentioned that irrigation allows a regular supply of water in drought seasons and it ensures the possibility of a better return of yield. As participant A120 stated:

> . . . here had quite sand, not basalt soil, it's quite sandy soils but they are very large open plains and very easy for irrigation, so you can put big pivot irrigators, so they've already been cleared, and it's basically ready for farming. Probably with irrigation and with suitable fertilisers, could be quite a productive area.

As well, participant A115 mentioned:

> Waterhouse was never considered a dairy area, and the reason for that is it's sandy. If you get any rain, it dries out really quickly, and without irrigation, it just doesn't work.

The interview findings affirmed that the availability of irrigation is an important decision factor for farmers to consider alternative crops/livestock. If irrigation is available and accessible for farmers, they can calculate the marginal profit of the crops/livestock, and then choose the crop type, which pays the costs, e.g. irrigation. The availability of irrigation provides an opportunity to change farm practice in the areas where the soil is not suitable for rain-fed agriculture and crop production that depends on rainfall for water.

Theme 5: Neighbour's decision effects as an influential factor for investing in irrigation, alternative crops/livestock

There is a level of interdependency between economic decisions of neighbours who share spatial space (neighbourhood), that form part of their network, interact with each other, and/or have similar social backgrounds (Anselin 2003; Ioannides & Topa 2010; Manson et al. 2016). The literature (and particularly on the diffusion of innovation) shows that farmers' decisions and behaviours are most impacted by their neighbours' decision and outcomes (Conley & Udry 2010; Tsusaka et al. 2015). Interviews with both farmers and other stakeholders corroborate the evidence of an inter-dependency between a farmer's decision and his/her neighbours' decision to change or adopt new practices such as to invest in irrigation and grow alternative crops/livestock. There is a relationship between a series of social variables such as neighbours' proximity effect (Vroege 2017) and the likelihood of adoption of new alternative crops/livestock or irrigation. This is also evidenced in the participant responses. As one of the respondents (A107) stated:

> I think farmers do look over the fence and see what other farmers are doing and think, 'Well, yeah, it'll be all right. No, I've just done it for so long. I'll just continue to do it the way I'm going to do it'. I think that that's, as I said before, it's a mindset.

In the Dorset region, it seems, farmers usually look at successful farmers and watch to see what they are doing. If the innovative and successful farmers try some new alternative crops/livestock through a new irrigation scheme and they succeed, the other farmers are more likely to follow them and adopt the new irrigation scheme. One of the participants (A116) noted that there is an interest in irrigation and change among some farmers, indicating that:

> We've got some innovative farmers in this area, but it's the same as every other area, the majority of them have to be led by the innovators. Personally, I'm always keen to try new things, but I think the Dorset region would be slow to move on most things.

Innovative farmers may have different values in comparison with other farmers (Vanclay 2011), and their farming operations might be completely ground-breaking and unexpected for other farmers. The location of the farmers' land determines their social network and who their neighbours are. When the innovative farmers have a successful enterprise, then the innovations such as irrigation might be adopted by their neighbours (Wright, V 2011). The evidence from interviews suggests that farmers in the Dorset region do take suggestions from their friends and neighbours, especially successful neighbours who invest in irrigation and grow new alternative crops/livestock.

Theme 6: Availability of three-phase power as a decision factor

In the Dorset region, some districts and areas do not have access to three-phase electric power. Three-phase electric power is an important infrastructure need and supports large development, whether it be in the agriculture sector or in other industries. Based on the interview findings, if there is not three-phase electric power available, it is challenging for farmers to invest in irrigation substantially, because grid supplied three-phase electric power is a lower-cost source of energy for irrigation systems.

Therefore, farmers need to consider their irrigation investment carefully as it can be risky to expand without access to three-phase power. Fifteen participants (nine farmers and six other stakeholders) mentioned that access to three-phase electricity is a decision-making factor. However, it is a complex decision factor as is illustrated in the points raised by one of the respondents (A103):

> The powers are a completely separate issue. The irrigators need to deal with the power companies. Most areas have adequate power, but there are some areas in the Scottsdale scheme, in the North East, in the Waterhouse area, that's Waterhouse is up here.. . . To further develop.. . . Or they need water for one thing, but if they're going to say, put in a dairy or something like that, they need the power as well.

And as another participant (108) mentioned:

> There's single-phase power there now.. . . There are people out there that have got pumps, and they have got irrigation. But it is much more expensive. It's a lot more expensive to operate it all. So, if they could get their 3-phase power out there, it would make it a lot cheaper for them. I believe that all the people out here, I think about one-third of the water, is going to go out to there.

The availability of grid supplied three-phase electricity determines the feasibility of using irrigation by reducing operating costs of irrigation systems. Access to three-phase electric power was therefore identified as an important factor for farmers who consider investing in irrigation in the Dorset region, especially in the Waterhouse and the North East areas (as per these comments).

Theme 7: Accessibility of value-add processing plants within a reasonable distance as a decision factor

There have been several processing plants for vegetables and milk in the Dorset region over past years, but most are now closed due to efficiencies that did not match global competition. In general, the participants' view was that large-scale processing plants are not going to invest in their region in the short term because of poor economies of scale and the lack of scale in agricultural production. As participant A109 noted:

> I don't think we're going to see another Simplot factory or another Fonterra milk factory in Scottsdale, in Dorset, anywhere soon.

Nevertheless, participants are aware that processing can value-add current crops/livestock production in their region. Interviewees mentioned that the cost of transportation and the distance from the farm gate (Dorset region) to the market (e.g. Melbourne or a processing plant) also have impacts on any decision about new alternative products or investing in irrigation schemes. Participant A105 stated:

> In theory, distance means that bulk commodities are not really viable, and we see that with some of the other industries here that you pretty much need a subsidy to transport the goods. If we can value add them, . . . if good planning and management are in place then yeah, and looking outside of the box and outside of those traditional crops, then yeah, it's possible.

Consequently, farmers considered the availability of and accessibility to value-add processing plants as a deciding factor in whether to grow alternative crops with a particular use. Several points raised by respondents highlighted that transport costs and access to processing plant affect farmers' decision on alternative crops/livestock. As participant A103 mentioned:

> Transport costs and time is quite a big factor.. . . Maybe, if through irrigation, they have significantly increased volumes of both milk and vegetables produced in the area that would then drive a processing plant to say, 'Well, it's now worthwhile, having a factory in the town'.

Based on participant insights, the Dorset region could be a more prosperous region, if farmers could have access to local factories to process their crops, vegetables or milk and therefore gain opportunities to value-add beyond the farm gate. A participant 114 stated:

> I genuinely believe if we could have a plant here locally again, to process those vegetables, and the marketing was done correctly, it would be a winner. There's no doubt about it.

Thus, with the right focus and set up for the appropriate scale, participants suggested that processing plants for the region could be profitable for the region and the local farmers. As Table 4-2 shows, participants proposed different options for a processing plant for the Dorset region. For example, around 47% of participants (farmers and other stakeholders) argued that milk product processing is feasible in the Dorset region, followed by vegetable processing (26%). Alternatively, Microwave-Assisted Thermal Sterilisation (MATS) (Regional Development Australia Tasmania Committee (RDA) 2016) or a winery were suggested as alternative processing facilities that could be considered on a small scale.

Table 4-2 Suggested value-add processing for the Dorset region

Suggestion for value-add processing plant in the Dorset region	**%**
Milk product processing	47%
Vegetable processing	26%
MATS	11%
Winery	11%
Hemp processing	5%

Overall, the interviews with farmers and other stakeholders revealed that the availability of value-added processing in the Dorset region could affect farmers' decisions to grow/produce alternative crops/livestock. The interview findings have indicated that a niche value-adding processing would be feasible particularly for a collective or a cooperative processing plant in the Dorset region.

Theme 8: Possible alternative crops/livestock with the potential to attract farmers' investment

Participants were asked to suggest alternative crops/livestock that could foster further investment in irrigation schemes and add value to the region. Most of the participants emphasised dairy and beef as profitable livestock and the right choices for farmers in the region. Many participants also noted that milk/dairy products and livestock are the most attractive options for the farmers and participant A116 noted:

> Dairy is taking the hit at the moment, but they are big investors when the dairy price is reasonable.. . . Beef prices are really good at the moment. The way beef prices are at the moment, you can afford to irrigate good pasture, to fatten those beef cattle.

Participants also mentioned some new alternative crops/livestock options such as hemp, viticulture, cherries and goat milk. Participant A118 noted:

> There's an opening for, hopefully, we can get some industrial hemp and even medicinal cannabis. I think those sorts of things have to be researched and I think there's a big thing in the North East for that.

The interview data pointed to the potential for some alternative crops/livestock in the Dorset region but noted beef and sheep, milk/dairy, potato, and poppy as the most important products. Other alternatives such as hemp, fruit (cherries), cannabis and goat milk were cited by participants in the survey.

Summary

Table 4-3 summarises the theme findings, highlighting the major themes and the frequency of the themes. Further details summarised in Appendix 2 include a comprehensive table that sets out: (1) the themes in the context of the research questions, (2) the meaning of the themes, and (3) the evidence to support the themes. It is important to note that these findings are not 'representative' of actual production activities in Dorset, but instead are designed to provide insights into the kinds of factors that influence farmers' decision making. The initial findings around these factors provide a useful and practical starting point for a conceptualisation of decision-making (agents) for a spatial ABM. That said, and importantly, these themes extracted from the semi-structured interview results are widely supported in the literature (Berger 2001; Diederen et al. 2003; Millington 2012; Sutherland et al. 2012; Manson et al. 2016).

Table 4-3 Frequencies of the major themes from interview participants

Major Theme	**Suggestions**	**Frequency (%)**
Theme 1: Positive futures for agriculture in the Dorset region		95%
Theme 2: Characteristics of the farmland		100%
Theme 3: Profitability and market price of alternative crops/livestock as a decision factor		79%
Theme 4: Irrigation availability as a decision factor		84%
Theme 5: Neighbour's decision effects as an influential factor for investing in irrigation, alternative crops/livestock		37%
Theme 6: Availability of three-phase power as a decision factor		58%
Theme 7: Accessibility of value-add processing plants within a reasonable distance as a decision factor	Milk product processing	47%
	Vegetable processing	26%
	MATS	11%
	Winery	11%
	Hemp processing	5%
Theme 8: Possible alternative crops/livestock with the potential to attract farmers' investment	Current crops (dairy, beef, potato, poppies)	63%
	Hemp	37%
	Fruit	26%
	Grapes	16%
	Goat milk	11%

Summarising briefly, the main factors that influence the farmer's decisions on investing in irrigation and new alternative crops/livestock are the biophysical characteristics of the land, the profitability and gross margin of the crops, the availability of irrigation, the neighbour's decisions, and the availability of three-phase power. The accessibility to plant processing is also important for this region. While most of the participants continue to support the traditional crops/livestock, nevertheless they are open to some alternatives such as hemp as a new alternative crop for the region.

4.3.2 Further investigation of the themes

Alongside the interviews, all the participants were asked to complete a formal survey. As Chapter Three outlined, the aim of the survey questionnaire (Appendix 3) was to extend the knowledge gained in the interviews as well as to triangulate the data. All 19 participants were surveyed after the interview. They answered thirteen questions including multiple-choice questions, open-ended questions, and one spatial question.

The analysis of the quantitative data was undertaken using Microsoft Office Excel software. Descriptive statistics were generated from the survey data, including scale average, percentage and frequencies of responses. NVivo software was again used for content analysis of written responses in the survey. Similarly, codes based on themes and patterns were identified within the written responses for content analysis.

As outlined in the methodology chapter, the survey questionnaire was categorised into three sections or provocations, in order to identify the points of convergence with the interview themes. The three aligned thematic areas pursued further were:

- The possibilities for the future of Dorset region
- Alternative crops/livestock for the region

- Key factors that influence farmers' decisions on growing alternative crops/livestock in the Dorset region

Having now identified themes of alignment areas between the interview findings and survey questionnaire finding, the three key areas were framed as provocations to explore possibilities that could then be later reflected in the simulations.

Provocation 1: The possibilities for the future of Dorset region

In the opened ended componenet of the survey participants were asked to 'map' a scenario for Dorset's future and rank the three main possibilities. To do this, the participants ranked statements about the future of Dorset region and the crops under irrigation and whether they agreed or disagreed. Table 4-4, for example, demonstrates the possibilities for the future of the Dorset region.

Table 4-4 Possibilities for the future of the Dorset region

	Dorset future	**Statement**
Possibility 1	no change	In the next ten years, if irrigation is expanded, the Dorset region would continue to produce traditional crops/ livestock.
Possibility 2	partially change	In the next ten years, if irrigation is expanded, the Dorset region would partially produce alternative crops/ livestock.
Possibility 3	partially change with regards to the processing plant	In the next ten years, if there is a cooperative of growers linked to a processing plant within the area, the Dorset region will produce half traditional crops/ livestock with half alternative crops/ livestock by irrigation expansion.

Figure 4-5 summarises the responses to these possibilities. Most of the participants (68%) were agreed on the second possibility (partially change in the agricultural sector) as a possible future for the Dorset region.

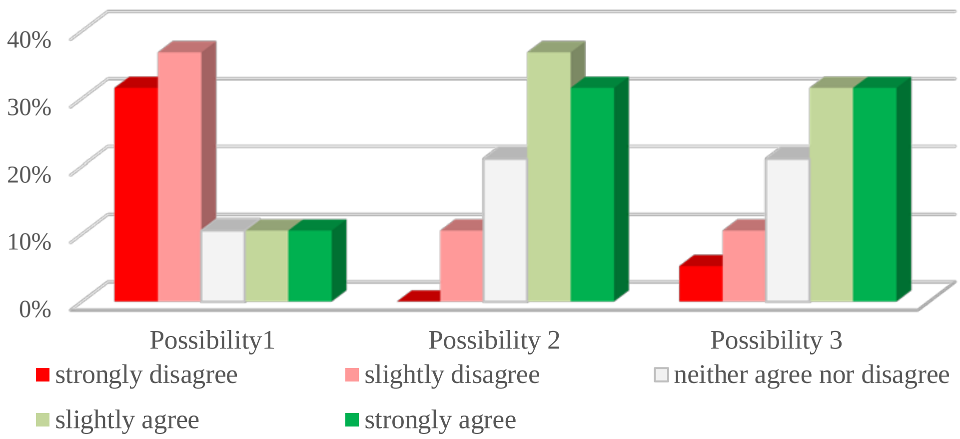


Figure 4-5 Possibilities for the future of the Dorset region

This suggests that, if irrigation is expanded in the Dorset region, alternative crops/livestock will be produced in the next ten years and that most of the participants accepted partial change in the region. Indeed, Figure 4-5 also demonstrates a willingness to change because the second scenario for the region (partially change) was ranked first by participants, closely followed by the third scenario (partially change with regards to the processing plant) and the first scenario (no-change).

<u>Provocation 2: Alternative crops/livestock for the Dorset region</u>

The second provocation in the survey questionnaire was to identify the top three alternative crops/livestock the participants' suggested for consideration. As Figure 4-6 illustrates, participants ranked milk and dairy, livestock (beef/sheep) and potato as the most important products that could be produced in the Dorset region. Poppy, vegetables and onions followed these top three ranked products. Interestingly, the top-ranked crops/livestock are the traditional products that have generated the region's reputation for quality.

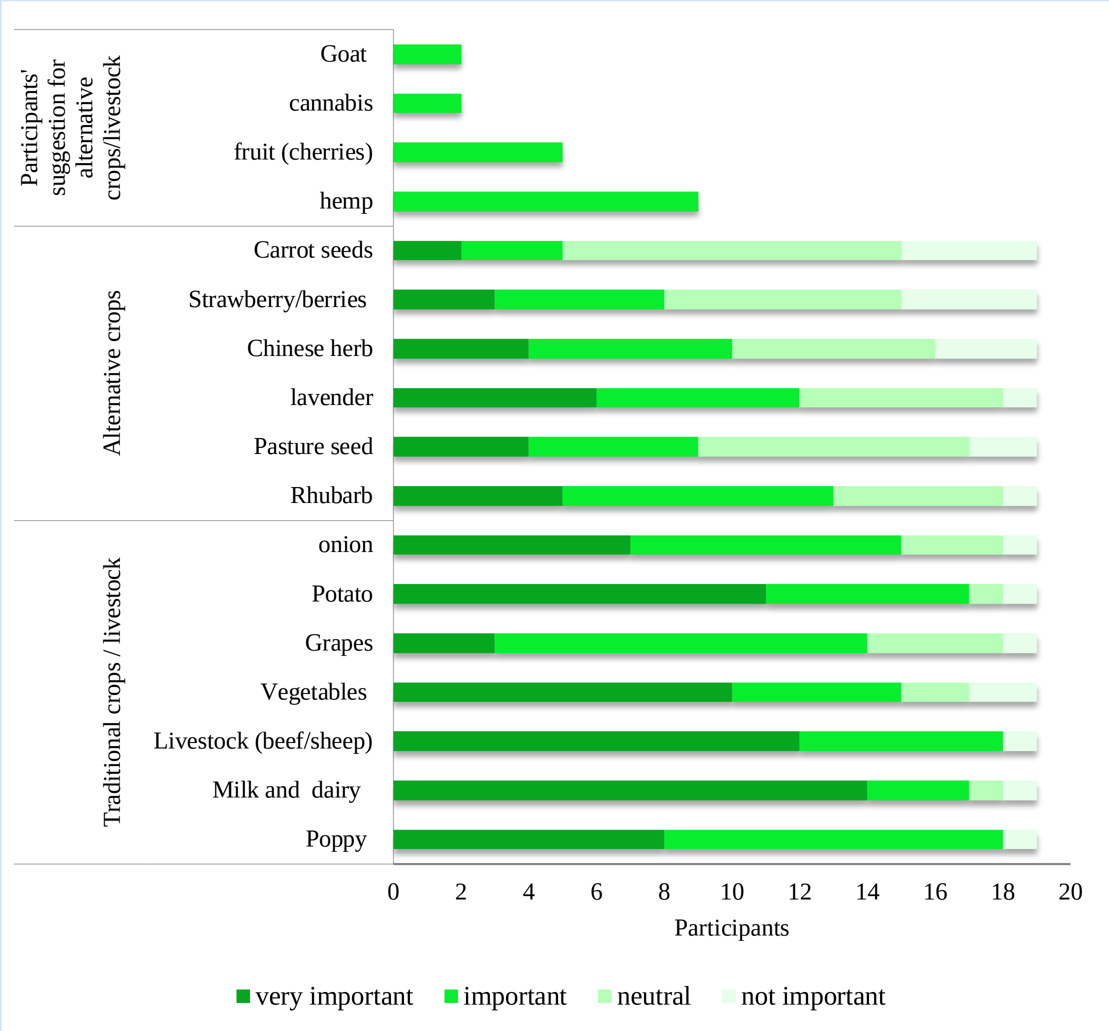


Figure 4-6 Important crops/livestock to produce in the Dorset region according to survey questionnaire response

As far as alternative crops are concerned, rhubarb and lavender were ranked higher than others probably because both crops have been 'successful' in recent years and brought new value-add to products and tourism to the region. But this data also suggests that there was an 'appetite' for some new crops/livestock in the Dorset region including berries (strawberries), Chinese herbs and pasture seeds. Yet more alternatives were suggested by participants such as hemp, fruit (cherries), cannabis and goat milk (see Figure 4-6).

Provocation 3: Key factors that influence farmers' decision on growing alternative crops/livestock in the Dorset region

It is important to stress again that these questions and the analysis of responses is designed to extract and clarify the factors that affect farmers' land use decision making. The conceptualisation of these farmer decision factors constitutes the critical building blocks for designing a spatial ABM system. Descriptive analysis was used to provide added depth to the initial insights on the most important factors. Following the possibility of growing new alternative crops, participants were asked to rank the most influential factors that inform their decisions about crops/livestock. The levels of importance of which factors influence farmers' decisions are summarised in Table 4-5.

Table 4-5 Factors influencing farmers' decisions on crop (Survey Responses)

	Factors	**Total score**	**Ranking**	**Remark***
Economic factors	Transport costs to market	69	3	high
	Transport costs to the nearest processing plant	67	5	high
	Government support/subsidy	46	13	low
	Irrigation costs	68	4	high
	Profitability	75	1	high
	A forecast that demands processing products is going to increase	60	8	moderate
	Labour availability	60	7	moderate
Social factors	Neighbour's decision about growing alternative crops/ livestock	49	9	moderate
	Experience of growing alternative crops	48	11	low
	Popularity of alternative crops/ livestock among farmers	49	10	moderate
Environmental/biophysical factors	The perceived environmental benefit	47	12	low
	Farm and land capacity	63	6	moderate
	The local climatic conditions	70	2	high

*Remark: "high" = 1 ≤ ranking ≤ 5; "moderate" = 6 ≤ ranking = ≤10; "low" = 11 ≤ ranking

The analysis of the statements outlined by participants in the survey identify factors similar to those outlined in the interviews and emerging themes. A 4-point Likert rating scale

(Croasmun & Ostrom 2011) was utilised for the results of the analysis. It showed that ten factors were rated moderate to high and three factors were rated low in influence.

Five factors were rated 'high' in influence, including profitability, the local climatic conditions, transport costs to market, irrigation costs and transport costs to the nearest processing plant. The factors seen as 'moderate' in influence include social, economic and biophysical conditions as ranked at the top of this group. A total score of more than 65 (where the total score is 76 in this study) indicates a considerable consensus among the participants' insights as being 'high' as an influential decision-making factor.

The highest score of 75 across all statements was associated with the profitability factor and showed that the participants were more consistent in their ratings in this than for the other factors. Thus, 'profitability' was identified as the most influential factor. With this evidence it could safely be assumed, for example, that the gross margin of the crops/livestock as a 'measure' of profitability can provide a simple method for comparing farm performance. That said, other factors such as the local climate conditions (e.g. drought) and transport and irrigation costs do play important roles in influencing farmers' decisions.

4.4 Merging qualitative and quantitative findings: scale, values & assumptions

Having identified factors that influence decision-making, the next step was to create a coherent and logical framework within which to 'merge' these factors. For this study, it is argued that a logical framework involves firstly the important factors that influence farmers drawn from merged interpretation of interview and survey questionnaire findings and secondly the scale at which the decisions are made and the interrelationship between scales. This is done because the design of a spatial ABM depends on understanding the scale and process of agricultural decision-making to assist in determining possible investment options (e.g.

irrigation) through scenario testing. It is important to note that these decisions occur at both micro and macro scales.

A key objective in conducting both interviews and a survey questionnaire was to triangulate qualitative and quantitative analysis of responses. The question then becomes, how does the cognitive nature of the more qualitative insights fit with the more analytical survey data. Integration of the interview and survey data provides an in-depth and better understanding of the process of farmers' decision-making. In the following sections, two scales of decision-making and the major influential decision factors on agricultural land and water use are discussed.

4.4.1 Merged interpretation – identifying the most influential decision factors

The purpose of the first stage of this research was to design a conceptual model of farmers' decisions. The process thus far has outlined in some detail the analysis of relevant data to identify factors and conceptualising the farm-based decision-making process for a spatial ABM. It was determined that these factors operate at micro and macro scales and some factors that are more important than others. The conceptual model needs to simplify the process of decision-making on agricultural land and water use by utilising the most influential factors, remaining cognisant of the macro and micro scales where these decisions are applied.

Based on the interview findings and discussed earlier, the key factors that affect farmers' decisions on irrigation and alternative crops/livestock are summarised again (Table 4-6).

Table 4-6 Key themes identified from the interview findings

Major themes
The characteristics of the land
The profitability and market price of alternative crops/livestock
Irrigation availability
Neighbour's decision for investing in irrigation, alternative crops/livestock
The availability of three-phase power
The accessibility of value-add processing plant

Similarly, analysis of the survey questionnaire data illustrated the ranked factors that influence farmers' decisions on irrigation and alternative crops/livestock. Table 4-7 summarises the most important factors as ranked by participants:

Table 4-7 Key factors identified from survey findings

	Major factors
Rank 1	The profitability
Rank 2	The local climatic conditions
Rank 3	Transport costs to market
Rank 4	Irrigation costs
Rank 5	Transport costs to the nearest processing plant
Rank 6	Farm and land capacity
Rank 7	Labour availability
Rank 8	A forecast that the demands for processing products are going to increase
Rank 9	Neighbour's decision about growing alternative crops/livestock
Rank 10	The popularity of alternative crops/livestock among farmers
Rank 11	Experience of growing an alternative crops/livestock
Rank 12	The perceived environmental benefit
Rank 13	Government support/subsidy

By comparison of Table 4-6 and Table 4-7, there is similarity across a set of factors that were extracted from interview findings and a set of ranked factors that were drawn from questionnaire survey analysis. For the purpose of this study, it is proposed that these sets of influential factors be merged into three categories: (1) biophysical, (2) economic and (3) social factors and Table 4-8 illustrates how the two data sources support this grouping.

Table 4-8 Grouping and merging interview themes and survey questionnaire findings

Major categories	**Factors from the interviews (themes)**	**Factors from surveys**
Biophysical environment factors	Characteristics of the farmland	Local climatic conditions (rank 2) Farm and land capacity (rank 6) The perceived environmental benefit (rank 12)
Economic factors	Profitability and market price of alternative crops/livestock	Profitability (rank 1) Transport costs to market (rank 3) Labour availability (rank 7) A forecast that the demands for processing products are going to increase (rank 8)
	Irrigation availability	Irrigation costs (rank 4)
	Availability of three-phase power	Government support/subsidy (rank 13)
	Accessibility of value-add processing plant	Transport costs to the nearest processing plant (rank 5)
Social factors	Neighbour's decision for investing in irrigation, alternative crops/livestock	Neighbour's decision about growing alternative crops/livestock (rank 9) The popularity of alternative crops/ livestock among farmers (rank 10) Experience of growing alternative crops (rank 11)

Grouping the themes into three broad categories (biophysical , economic and social) suggests, not suprisingly, that there is a connectedness across some of the factors identified from the interview analysis and survey questionaire findings. Figure 4-7 seeks to illustrate the connectedness of factors raised by the participants, that is, the connectedness of the interview themes and the survey questionnaire findings, and the grouped influential factors for farmers' decision-making.

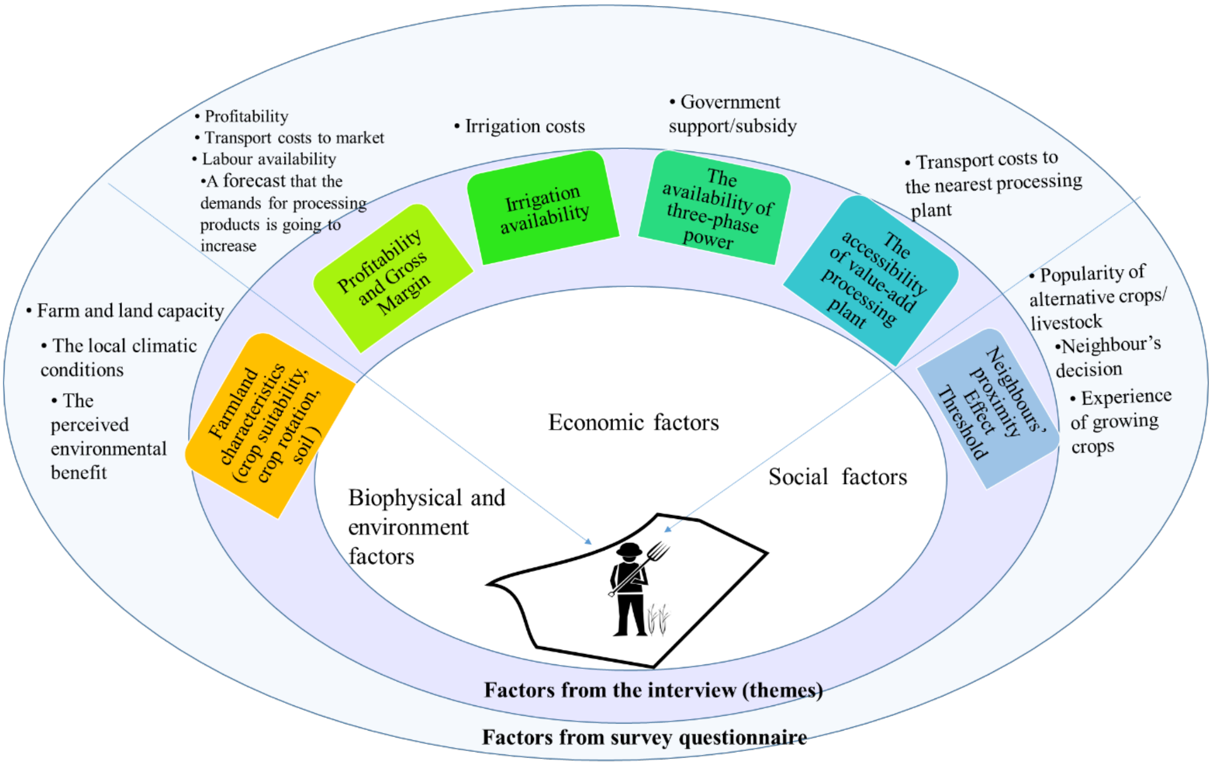


Figure 4-7 Connectedness of the interview themes and survey questionnaire findings of key influential factors for farmers' decision-making

Respondents to the survey questionnaire ranked the biophysical and farmland characteristics (e.g. soil, slope, drainage and stone) and the profitability of the agricultural enterprise higher than other themes, which indicates the importance of these factors in the decision-making process. The availability of irrigation is another important factor for decision-making on crops/livestock production. Other economic factors such as the availability of three-phase power and the accessibility of a processing plant are also influential factors. Most of the participants mentioned that neighbours' decisions on adoption of irrigation schemes or new alternative crops/livestock influence farmers' decisions, and the survey findings supported the neighbours' proximity as another influential factor for decision-making.

4.4.2 Two scales of decision making – a framework for merging decision factors

To this point the analysis of data and discussion has been directed at farmers and farmers' decisions. But these decisions can also be undertaken at a macro scale such as the region.

Decision-making regarding the implementation of change in farming practice such as new irrigation resources at the regional scale is also a complex process and involves consideration of different stakeholders such as farmers, local government, State irrigation bodies and the food processing industry.

Analysis of the survey and interview data suggested that the stakeholders could be categorised in two major groups based on the decision makers' characteristics and the scale of their decisions, e.g. regional scale (macro level), and farm scale (micro level). This is set out in Figure 4-8, which describes the general characteristics of their viewpoints and their decision-making process in the context of change, such as alternative crops/livestock and/ or irrigation expansion.

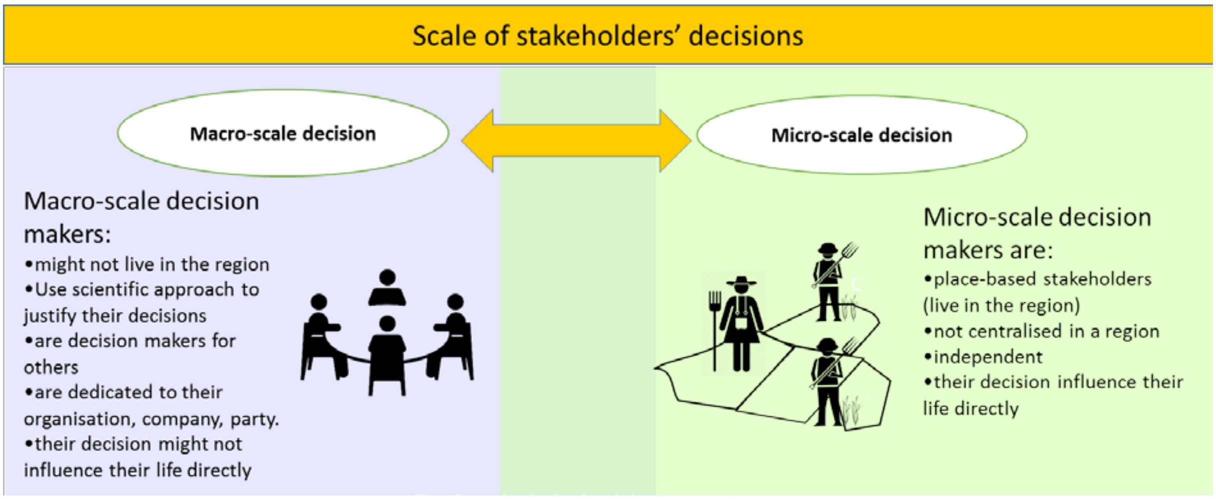


Figure 4-8 Stakeholders' characteristics for deciding on land and water use

One one side, micro-scale decision-makers are the farmers. Farmers make independent decisions about what to grow, where to grow it and how much water they need (Food and Agriculture Organization of the United Nations (FAO) 1993). Their decisions are shaped by both the opportunities available in their region (e.g. potential for irrigation infrastructure), and their knowledge of the land, their experiences and technology. Farmers are very much place-based stakeholders. While located across the region, they mostly make their decisions independently, based on their knowledge and experience, and availability of information on irrigation-related investment and its likely direct impact on their income. Farmers therefore decide on land use, crop types and irrigation, and for this study farmers are micro-scale decision-makers.

However, the other group of stakeholders in agricultural decision-making are the companies and state government-owned bodies and local government who also make decisions about water, land use and irrigation expansion but at the macro scale (regional scale). Indeed, they might not even live in the region. Their decisions affect many people who live in the Dorset Region. Their decisions are often based on a scientific or business approach to livelihoods and income, and their judgments or decisions are more likely designed to justify benefits for their organisation. Further, these decisions more often do not affect their lives directly. For this study, they are macro-scale decision makers.

There is a relationship between macro-scale and micro-scale decision-making process. For instance, the State government irrigation bodies make a decision on the expansion of irrigation in the region (macro-scale decision), and the availability and accessibility of irrigation influences farmers' decisions on crop types (a micro-scale decision). On the other hand, farmers decide where and how to invest, including whether to buy into the irrigation scheme, so their micro-scale decisions also influence the future of irrigation expansion in the region. Therefore, if the Spatial ABM can incorporate decision-making factors at both scales it affords an opportunity to reflect the macro- and micro-scale decisions interactions and relationships in the simulations and scenario testing.

4.5 Conceptualising farmer decision-making

The purpose of the first stage of this research was to design a conceptual model of farmers' decisions around alternative crops/ livestock and irrigation expansion. In developing the model, it is argued that the conceptual model must be amenable to input from both macro and micro levels of stakeholders and that the conceptual model needs to be underpinned by shared assumptions among different stakeholders' considerations about the irrigation expansion and alternative crops. By understanding the characteristics of the decision-makers, the scale and the influence of their decisions, the choices they make (e.g. traditional and alternative crops/livestock) and their values, it becomes possible to develop some assumptions for designing the decision model.

The conceptual model has necessarily simplified the complex process of decision-making on agricultural land and water use, but it simultaneously covers the important, influential factors for the decision-making process (Figure 4-8). Based on the combination of qualitative and quantitative factors, it is possible to suggest the following 'set' of the decision-making process, for example, the sequence of decision-making that a farmer may go through for deciding on alternative crops/livestock. Figure 4-9 illustrates a possible conceptualisation of a sequence of decision steps based on a set of important and influential factors.

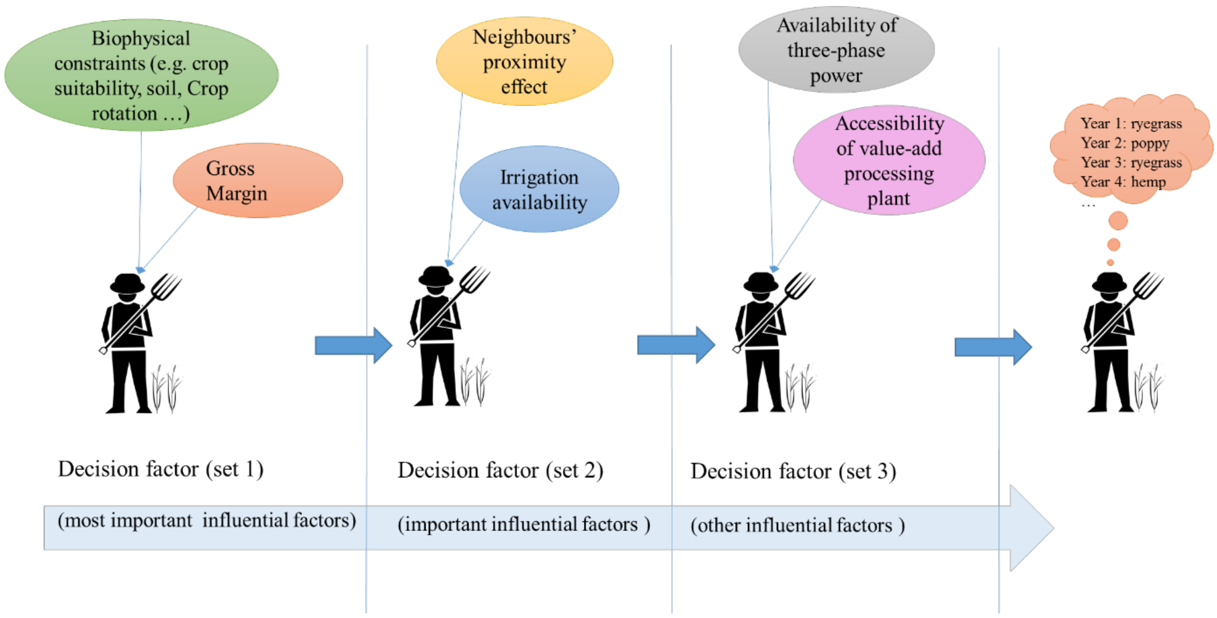


Figure 4-9 Conceptualising farmers' decision model based on influential factors

Farmers as micro-scale decision-makers decide on crop type and irrigation based on a set of influential factors such as crop suitability to their land, gross margin of the crop, the availability of irrigation, the rotation of crops and neighbours' proximity effect factors. However, there are some macro-scale decisions such as land-use policy, the market price and irrigation expansion area that affect farmers' decisions on crop types and investment in an irrigation scheme. These decisions are not controlled by farmers, yet the accumulated decisions of farmers could affect the macro-scale decisions on irrigation expansion in different districts of the region in the long term. As a result, the relationship between two scales of decision-making needs to be captured by building a spatial ABM based on the conceptual model of farmers' decisions.

4.5.1 A note on the validity of the conceptual model process

Several mechanisms were established to ensure credibility and transferability of the qualitative data and findings. Monitoring of interview processes, triangulations, and the NVivo software have been used for this purpose. The researcher personally conducted and recorded the interviews for transcription purposes. A data collection calendar was developed as a useful monitoring exercise to track the interview process. After transcription of the recorded interviews, the transcripts were read and compared multiple times with the audio recordings to ensure that the data was accurate.

Conducting a semi-structured interview and a survey allows for comparison of responses by different stakeholders with different insights. Further, the major themes that emerged from the interview were compared and triangulated to participant responses to the questionnaire to ensure different types of data led to the same finding. Finally, NVivo software was used to help to integrate the qualitative and quantitative data and to reduce the misrepresentation of information.

As a part of triangulation, the interview and survey results were compared with the existing literature. There is a similarity between influential factors that affect farmers' decision in this study and Macquarie Franklin (2013). According to the report by Macquarie Franklin published in 2013, higher price was a major factor influencing farmer's decisions to grow poppies which are aligned with the economic factors in this study findings. Irrigation infrastructure was also found as an influential factor in the aforementioned report which found in this study as an important factor that influences farmers decisions. According to literature (Sutherland et al. 2012; Vroege 2017), the neighbourhood effect is an influential factor that affects farmers' decisions. As Tsusaka et al. (2015) describe, there is are stronger neighbourhood effects among farm plot neighbours, which is aligned with the neighbour's proximity effects that found in this study. Therefore, triangulation of research findings with other evidence, in this case literature, verify the robustness among interview and questionnaire inputs.

4.5.2 Summarising the first stage: conceptualising farmers' decision-making

The first question of this research (Q1) focused on finding the most important economic, social and environmental influential factors that affect farmers' decisions on crops/livestock choice and irrigation adoption. For this purpose, both qualitative data through semi-structured interview and quantitative data via questionnaire, were collected and analysed. Major themes and the most influential factors emerged from stakeholder insights, including the characteristics of the farmlands, the profitability and market price of the crops/livestock, irrigation availability, neighbour's decisions and proximity effect, and crop rotation. Merged interpretation of both qualitative and survey data also revealed that there are two levels of decision-making on agricultural land use, macro-scale and micro-scale. These two scales of decision-making interact with each other, and their decisions influence agricultural land use pattern change over time.

Chapter 5: Designing the simulation model (Stage 2)

In the second stage in the development of a spatial ABM simulation model, the conceptual model of farmers' land use decisions is carried forward to be integrated into the agent-based model and turned into elements, function and rules. The process by which this is done addresses the second question posed in this research:

- *(Q2)- How is social, economic and environmental data integrated with ABM in a GIS-based 'virtual laboratory'?*

ABM simulation algorithms are developed based on the conceptual model and computer codes are written based on the abstraction of the farmers' decisions model. The algorithms inform the development of the simulation model and the internal validity of the spatial ABM is checked.

5.1 Designing the algorithm

Designing an algorithm is the key step in developing a simulation model using computer programming language (Bhattacharya 2010). Figure 5-1 shows the role of an algorithm in transferring the conceptual model to a spatial ABM.

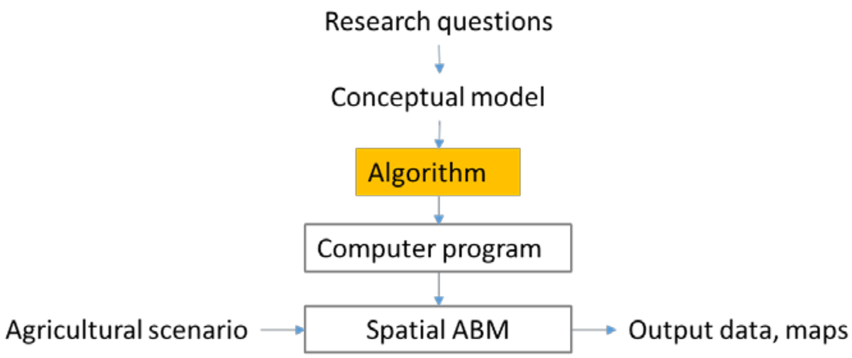


Figure 5-1 Algorithm's role in the design and development of spatial ABM

An algorithm is a linkage that facilitates the translation of a conceptual model (in this case, farmers' decisions) to a computer program and spatial ABM. Levitin (2012, p. 3) describes an algorithm as 'a sequence of unambiguous instructions for solving a problem'. An algorithm also provides a set of precise instructions and rules for performing a computation-based model – in this instance, in response to a conceptual model of farmers' decisions. Once an algorithm is designed, it can be translated into a computer program.

There are different methods for specifying and expressing an algorithm including pseudocode, well-defined programming language and flowcharts. Often the textual description of the algorithm is not easy to understand. Therefore, for this study, a computer program flowchart was employed as a representation of the algorithm. The flowchart is a diagrammatic representation of an algorithm's steps (Chaudhuri 2005).

The algorithm, in this study, was expressed in a flowchart format with specific symbols to describe a set of precise instructions and rules that must be implemented in the computer program. The process of designing the algorithm consisted of four significant steps, as illustrated in Figure 5-2.

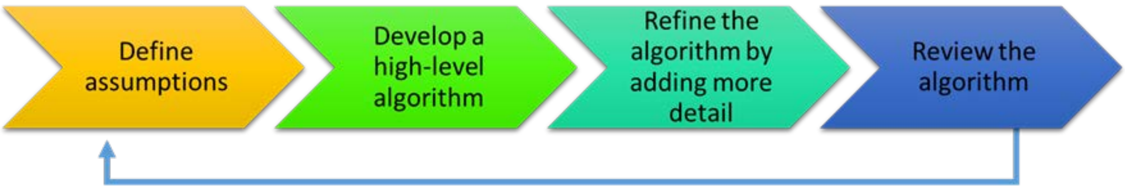


Figure 5-2 Four significant steps for designing an algorithm for this research

5.1.1 Define assumptions for designing algorithms

Section 4.1 (Stage one) discussed the stakeholders' perspectives and the influential factors for deciding on alternative crops/livestock options. Assumptions for designing the algorithms were then defined based on findings in stage one. The main assumptions for transferring the conceptual model of farmers' decisions to a set of instructions and rules written in the computer language included:

- Each area of farm land (land parcel) has a farmer who can change the farm practice
- Each farmer decides on his/her own parcels of land
- Farmer history and knowledge contributes to his/her future decisions
- There is a spatial relationship between the land parcel (and land use) and the broader pattern of the agricultural land at the regional scale
- The size of the farm is the area of each land parcel
- The Farmer agent's behaviour is fully informed and rational and is the optimal decision on crop type.

The Enterprise Suitability Maps (Department of Primary Industries Parks Water & Environment -Tasmania n.d.-b) were used as the basis of biophysical conditions in the model and linked to the land parcels. These maps were derived from a combination of local climate and land characteristics such as frost, winter chilling, summer heat, drainage, slope and salinity developed by DPIPWE (Department of Primary Industries Parks Water & Environment -

Tasmania n.d.-b). The assumption was that Farmer agents decide on crop type by considering climate and soil information. These assumptions imply that the algorithms need to be designed based on the recognition that there is an interaction between the farmer as a decision-maker, and the land use (land parcel) as a geometric and spatial component at the micro-level scale. But the algorithms also need to be designed to illustrate the geometric and spatial relationship between the farmers' decisions and the agricultural land use change (i.e. at macro-level). In other words, the algorithms need to take into account farmers' decision-making processes, the spatial relationship and the interactions of farmers with their farm land in order to answer the research questions about agricultural land use change. In response to these assumptions, two groups of rules were designed based on two levels of decision- making:

Macro-level rules: there were based on policy potential and opportunities in the region (e.g. irrigation infrastructure), as mentioned in Chapter One. Macro-level rules directly affect farmers' decisions for investing in an irrigation scheme and, for example, may offer encouragement in the form of subsidies for certain behaviours. An important assumption is that farmers cannot change these rules (at least in the short term) and they cannot control the decision-making process at the macro-level. For this study, examples of macro-level rules include:

- The land use policy determines the availability of land for agricultural uses.
- The market price of crops/livestock determines the farm's gross margin.
- The irrigation districts determine the availability and security of water in the areas to improve the productivity of the land.

Micro-level rules: There were decided from micro-level data derived from the interview and survey data. The micro-level rules are based on farmers' knowledge of land and water and physical constraints (e.g. land capability), crop suitability, farmers' personal and cultural values and their views and values about irrigation expansion. These rules can be changed by farmers through new conditions to suit themselves. Examples of micro-level rules may include:

- Land capability and crop suitability determine the type of crops/livestock and the amount of water that farmer agents need to overcome the constraints (such as soil, slopes) and to improve the productivity.
- The gross margin of alternative crops/livestock determines the farmer's attitude toward growing new products by considering margins of income.
- The irrigation availability based on the farm location determines the feasibility of changing the marginal land to suitable land for producing crops.
- Neighbours' proximity effects on each other's decisions and the surrounding fields determine the social network for investing in change or innovation such as an irrigation scheme and growing new alternative crops/livestock.
- Crop rotation determines the restriction of the production of one type of crop each year as a function of the previous year's crop or pasture.

5.1.2 Develop high-level algorithms

The algorithms need to consider both farmer (agent) and the farm (land parcel) as entities that interact with each other. Thus, spatial data such as GIS layers play a key role in linking the decision-making process (farmers' decisions) with the land parcel, i.e. agricultural land use and land use change over time. The aim of this step is to determine the input data needed for developing the algorithm and the start and end points in the flowchart.

Input data: The input data included maps (GIS layers), survey data (stakeholders' preference for top three crops/livestock), numerical data (census data, crop's gross margin). The GIS layer (shapefile) used in this study has different attributes that were extracted from various GIS layers and census information (for example from the Australian Bureau of

Statistics). Furthermore, it includes the biophysical information about the Dorset region such as crop suitability information, soil maps, slope maps, land capability maps, land use maps. These spatial data were developed by DPIPWE (Department of Primary Industries Parks Water and Environment Tasmania n.d.). The irrigation expansion districts are also GIS layers.

As outlined, the interview and survey data were analysed, and some values of predefined parameters were extracted based on the participants' insights. This information was then used to define some rules and parameters in the algorithms, such as the neighbours' proximity effect.

In the case of numerical data, some parameters and their predefined values were adopted from DPIPWE's published information sheets for the calculation of farmers' profit crops. For example, the gross margin of crops such as hemp, ryegrass, potato and poppy were extracted from DPIPWE reports (Macquarie Franklin 2012, 2018a, 2018b).

Starting and ending point: The flowchart method (Chaudhuri 2005) was used to illustrate the sequences of steps for developing algorithms for this study. Figure 5-3 illustrates the flowchart of the high-level algorithms for this study. It sets out a sequence of simple steps based on the main influential factors for deciding on crops/livestock and the computer logic structure for the farmers' decision model.

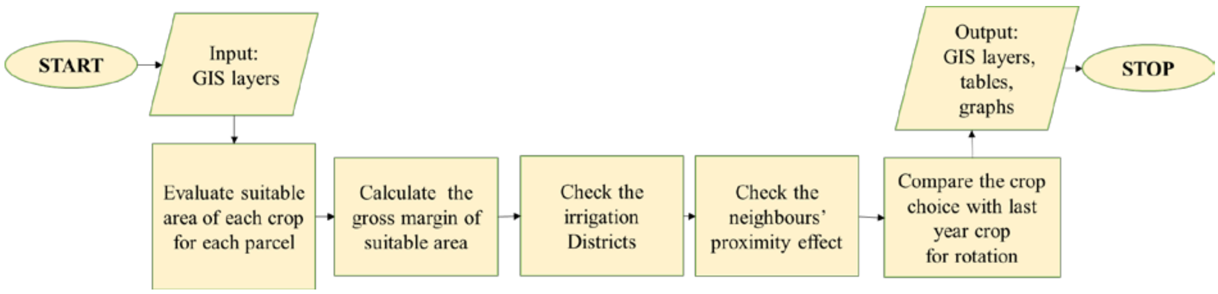


Figure 5-3 Flowchart of high-level algorithms

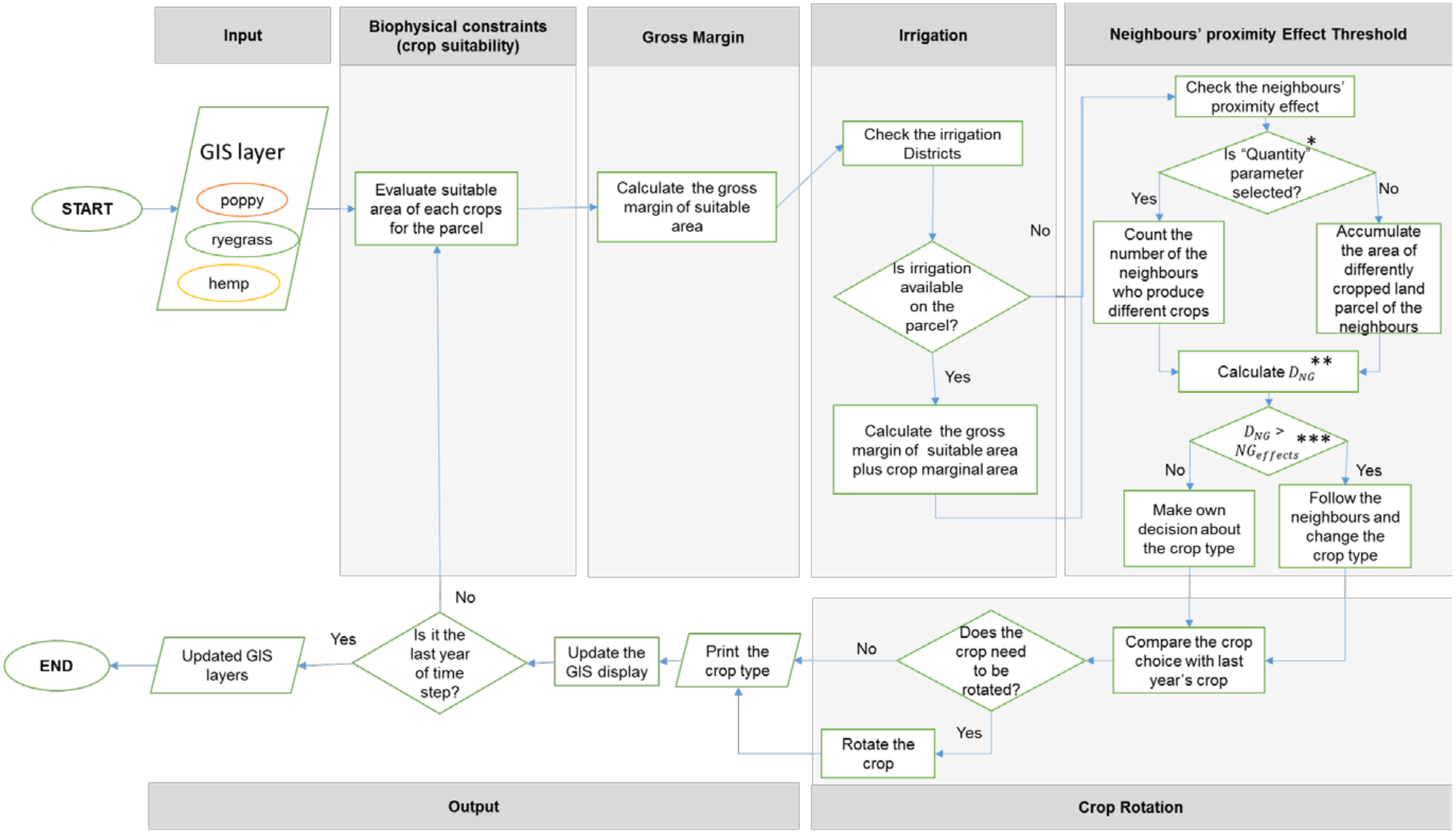
Flowcharting the farmers' decision model helped to articulate the sequence logic of a computer program. There are eight steps in the high-level algorithms that represent the farmers' decision-making process. The process starts with taking the GIS data and stops with the demonstration of the results of farmers' decisions in GIS displays, graphs and tables. Table 5-1 illustrates the high-level algorithms for designing spatial ABM in the Agent Analyst software. The table also demonstrates that algorithm's steps (Step 2 to Step 6) align with the important influential factors that affect farmers' decisions.

Table 5-1 Key steps implemented in the simulation model

Steps	**Description**	**Influential Decision Factors**
Step 1	Take the GIS layers to be analysed	
Step 2	Evaluate the suitable area of each crop for each parcel	Biophysical constraints
Step 3	Calculate the gross margin of the suitable area	Profitability Gross margin
Step 4	Check the irrigation availability	Irrigation
Step 5	Check the neighbours' proximity effect	Neighbours' proximity effect threshold
Step 6	Compare the crop choice with last year crop for rotation	Crop rotation
Step 7	Display the output as GIS layers, graphs and tables	
Step 8	STOP	

5.1.3 Refining the algorithms by adding more details

The main steps for developing a spatial ABM has been described in the high-level algorithms. The high-level algorithms then become the basis for adding more details and Figure 5-4 illustrates a flowchart of the detailed algorithms.



(*) It is a parameter that give the model-user a choice between Quantity or Area rules (explained in section 5.3.1)
(**) It is an equation that calculates a ratio of the differently cropped neighbour parcels to the total neighbours (explained in section 5.3.1)
(***) It is Neighbours' proximity Effects Threshold (explained in section 5.3.1)

Figure 5-4 Flowchart of detailed algorithms

The 8 steps in the high-level algorithm can be refined and are described in more detail as follows:

Step 1- Take the GIS layers to be analysed: the algorithm started by initialising Block agents and Farmer agent and parameters. Then the algorithms took variables and parameter values using a GIS layer attributes table.

Step 2- Evaluate the suitable area of each crop for each parcel: the suitable area of each crop was initialised to each parcel of land. The suitable areas were set then up for each Farmer agent.

Step 3- Calculate the gross margin of the suitable area: In this research, the gross margin indicates the gross income derived from selling the crop minus the variable costs associated with the enterprise. Farm gross margins consider all annual production costs and income of a particular crop on a per-hectare basis. The estimated gross margin for each crop, as identified by DPIPWE, was used as the basis for calculation of this model. In this study, the gross margin of each crop inside each parcel of land was calculated using the equation:

$$\boldsymbol{Gross\ Margin\ Decison\ \ (GM_D)}$$
$$= \boldsymbol{Crop\ Suitable\ area\ (per\ ha)\ *\ Gross\ margin(per\ ha)}$$

(Equation 1)

Next, the calculated gross margins of the suitable crops (e.g. poppy, potato and ryegrass) were compared, and the highest gross margin value crop was chosen for each land parcel.

Step 4- Check the irrigation availability: Based on the interview findings, if irrigation is available, farmers are able to increase their yields and intensify their crop productions. The irrigation decision was modelled to calculate the gross margin of the suitable area and the marginal area of the crop in irrigation districts. If the land parcel was outside the irrigation districts, the decision would be based on the gross margin of the crops. If the land parcel was inside the irrigation districts, the farmers would be able to intensify their crops and convert the land with rain-fed soil (marginally suitable for crop production), to a suitable area by irrigation. The equation is:

$$\boldsymbol{Irrigation\ Decison\ \ (Irri_D) =}$$
$$[\ \boldsymbol{Crop\ Suitable\ area\ (per\ ha) +\ Crop\ marginal\ area\ (per\ ha)] * Gross\ margin(per\ ha)}$$

(Equation 2)

Step 5- Check the neighbours' proximity effect: based on the interview data, it was established that farmers look at their neighbours' land parcel and evaluate the social networks around them, and that can be a catalyst to change their crops. In this model, neighbours are represented as parcels that have a border with a target parcel and share edges as well as vertices. The Queen Contiguity neighbourhood (Johnston 2013) is a continuity-based spatial weight method. This method was employed in this study to analyse the spatial relationships between polygons. It refers to which polygons are selected as neighbours for a single target polygon (Lloyd 2010) in the ESRI GIS software. It means that the polygons that share edges and vertices are neighbours and the distance from the target polygon determines the neighbourhood and the neighbours' relationship (Johnston 2013).

In this algorithm, the Neighbours' proximity Effects Threshold ($NG_{effects}$) estimates the influence of social interaction and neighbours' decisions effects. The model-user can modify the ($NG_{effects}$) based on the social interaction and the region characteristics. The Queen Contiguity was used for defining the neighbourhood.

In this model, F is a farmer agent who decides on a crop type. The farmer agent may change the crop type and choose the new crops if the number of the parcel area of surrounding neighbours who produce new crops are higher than his/her threshold ($NG_{effects}$). Each farmer F_i therefore checks the direct farmer neighbours NG_i and counts the number of neighbours who produce crops that are different from his crop choice, or calculates the area of differently cropped land parcels of the neighbouring farms (NG_{diff}). Then, F_i calculates the D_{NG} as a ratio of the different cropped neighbour parcels to the total neighbours.

$$\boldsymbol{D_{NG} = \frac{NG_{diff}}{NG_{Total}}}$$

(Equation 3)

If $D_{NG} > NG_{effects}$, then F_i follows the neighbours and changes the crop type. Otherwise, the farmer agent is not affected by their neighbours' decisions and makes his own decisions about the crop type. In this model, there are two decision rules described as:

- Quantity is a function where the farmer agent compares the number of differently cropped neighbours' parcels to the total number of neighbours' parcels.
- The area is a function where the farmer agent makes a decision based on the sum of the surrounding areas of different crops.

These rules help the model-user to define how a Farmer agent interacts with the neighbours.

Step 6- Compare the crop choice with last year crop for the purpose of rotation: When a crop type is assigned to the parcels, each farmer agent first considers the rotation by checking last year's crop and compares it with the current crop type. If there is a need for crop rotation, the farmer rotates the crop to a suitable crop.

Step 7- Display the output as GIS layers, graphs and tables: at the end of each time step [3], the output of the simulation displays in ArcGIS software. After the final decision on crop type, the GIS layer attribute prints the crop type, the GIS layer is updated, and the ESRI

[3] A time step is the incremental change in time in equations. In this study the time steps are year by year for ten years.

GIS displays the updated maps. The data stores in a GIS shapefile and the process continues until the end of the time steps.

Step 8- STOP: at the end of each time step, the algorithm checks whether it is the last step or not. The algorithm stops at the end of the time-steps.

The details of each step and equations for implementation in spatial ABM are summarised in Table 5-2.

Table 5-2 Summaries of the detailed algorithms that were implemented in spatial ABM

Steps	**Description**	• **More Details**	**Equations**
Step 1	Take the GIS layers to be analysed	• Initialise the agents (Block agent and Farmer agent) and parameters • Take variables and parameters' value	
Step 2	Evaluate the suitable area of each crop for each parcel	• Identify suitable areas for each crop • Set up the suitable areas for each agent	
Step 3	Calculate the gross margin of the suitable area	• Identify the gross margin of each crop • Calculate the gross margin of each crop through Equation (1) • Set the calculated gross margin of each crop for each agent	$\text{Gross Margin Decision } (GM_D) = \text{Crop Suitable area (per ha)} * \text{Gross margin(per ha)}$ Equation (1)
Step 4	Check the irrigation availability	• Check whether Farmer agent is in the irrigation district • Decide on irrigation investment • Calculate gross margin of irrigated crops through Equation (2)	$\text{Irrigation Decision } (Irri_D) = [\text{Crop Suitable area (per ha)} + \text{Crop marginal area (per ha)}] * \text{Gross margin(per ha)}$ Equation *(*2)
Step 5	Check the neighbours' proximity effect	• Identify the neighbours of each agent • Evaluate what the neighbour's crop is • Calculate the threshold of each Farmer agent through Equation (3)	$D_{NG} = \frac{NG_{diff}}{NG_{Total}}$ Equation (3)
Step 6	Compare the crop choice	• Identify the last year crop	

Steps	Description	More Details	Equations
	with last year crop for rotation	• Decide on whether to rotate the chosen crop	
Step 7	Display the output as GIS layers, graphs and tables	• Change the display in ArcGIS software every time step • Store the output in a new GIS shapefile	
Step 8	STOP	• Check whether it is the last step or not • Stop at the last time step • Update the display in ArcGIS software	

5.1.4 Review the algorithms

The algorithms were checked to ensure they led to a computer program, aligned with the stakeholders' insights and answered the research questions. As Figure 5-5 illustrates, the algorithms designed in the previous steps reflected the conceptual model of farmers' decisions and took into account the important influential factors that stakeholders mentioned. This confirmed that the designed algorithms were not only aligned with stakeholders' insights on how farmers make decisions on crop type and irrigation, but also had the capability to be transferred to a computer program. Furthermore, the algorithms represented the farmers' decision model that was conceptualised from interview and survey data in the first stage, and it can be generalised to other regions similar to the case study region.

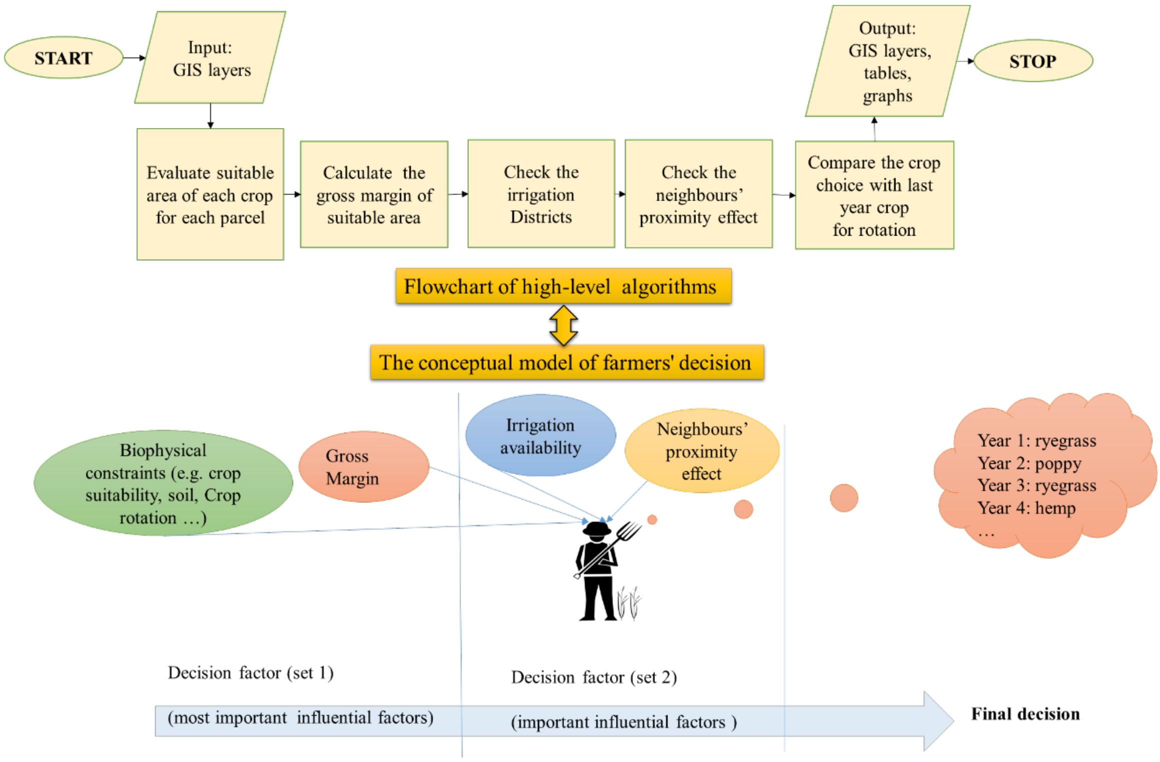


Figure 5-5 Checking the flowchart with the conceptual model of farmers' decision and algorithms

The algorithms designed for this study were the foundation for the researcher's development of a simulation model, named 'Crop GIS-ABM'.

5.2 Programming the algorithms

The algorithms designed in the previous section needed to be programmed to simulate the farmers' decision steps, behavioural rules and spatial interactions. The algorithms were transferred into Agent Analyst software (developed by Esri ArcGIS). Agent Analyst software was selected for two reasons. Firstly, Agent Analyst software effectively accommodated both the complex spatial structures in GIS and the rich, dynamic processes of ABM. Secondly, Agent Analyst provided flexibility and direct access from the coding environment to a GIS database and visualisation environment

The simulation model of farmers' decisions (Crop GIS-ABM) was programmed by the researcher in Agent Analyst software. The Crop GIS-ABM was built using Not Quite Python (NQPy) programming language[4] to define the agent's behaviour and interaction with a GIS-based landscape and topology. The Crop GIS-ABM is explained with details in the ODD+D protocol format in Appendix 5.

The ODD+D protocol is a standard protocol for describing ABMs (Grimm et al. 2010). The ODD+D protocol was employed to explain the process of designing Crop GIS-ABM in three sections including (1) the overview, (2) the design concept and (3) details of initialisation. The overview and some characteristics of Crop GIS ABM are now described in the following sections, and the details of the design concept and specific details of the model are explained in Appendix 5 in ODD+D format.

5.2.1 Overview of Crop GIS-ABM

Crop GIS-ABM is a spatial ABM that simulates complex dynamic interdependencies between farmers' decisions and regional land-use and crop pattern change. In particular in the Crop GIS-ABM, a farmer as an object-oriented entity responds to changes in his/her environment autonomously through a set of rules that link information about his/her environment to his/her decision. It integrates a vector polygon agent which includes available resources of the spatial and environmental dataset with a generic agent that contains human decisions criteria and social interactions. The Crop GIS-ABM represents an effort to bring the discrete components and factors together in a coherent simulation model.

The Crop GIS-ABM has four key features including two types of agents, sets of fields, sets of actions and schedules that are summarised in Table 5-3.

[4] NQPy is an object-oriented programming language and a subset of the Python programming language that used to implement actions in RepastPy (a java application). (http://repast.sourceforge.net/)(Collier & North 2004; Johnston 2013)

Table 5-3 Key features of Crop GIS-ABM

Key features	Descriptions
Agents	• Vector agent represents the land parcel (farm land). • Generic agent represents the farmers.
Field	• Defines variables and contains the data.
Action	• Contains the rules and functions that the agent can perform in the different time steps.
Schedule	• Controls the action executions over the time steps and specifies the order of the interaction with the other agents or the environment. The schedules organise when the agent's actions can be run.

The following sections consider the four features summarised in Table 5-3 in detail.

5.2.2 Agents: Farmer Agent and Block Agent

In Crop GIS-ABM, an Agent is a symbolised entity of the real world (e.g. land parcel) or an abstract concept (e.g. the farmer and their attitudes toward innovation adoption). There are two classes of agents in the Crop GIS-ABM:

Vector agent (Block agent): the vector agent is called a Block agent in the Crop GIS-ABM. A Block agent represents a spatial vector layer of cadastral polygons. Each polygon shows the locations of land parcels. The parcel can be updated after every year time step simulation, and its attributes may be altered when the model executes.

Generic agent (Farmer agent): generic agent in the Crop GIS-ABM is a Farmer agent. A Farmer agent represents an individual farmer who resides in the Block agent. A farmer decides on crop types, and the Block agent displays the farmer's crop choice year after year.

5.2.3 Fields: Variables and parameters

The fields contain the data that are available to agents. In the Agent Analyst software, the fields are the variables that can be set as model parameters and can be retrieved by the model-user (North, Collier & Vos 2006; Samuelson & Macal 2006). In Crop GIS-ABM, parameters are the conditions and attributes that supply the values to the model. The model-user can alter the input values of parameters and enter other values to simulate different scenarios of the model.

Parameters allow the model-user to set a different value for the Crop GIS-ABM. Some parameters (Time steps, Neighbours' proximity effect threshold, Ryegrass percentage and Gross margin) were stored in a numeric field (Double). In the Crop GIS-ABM model, there are also two Boolean model parameters (Irrigation availability, and Quantity/Area). The Boolean parameters are a conditional statement, which allows the model-user to choose between two decision rules. The model-user can alter the agent decision-making mechanism by changing the Boolean value (True and False). The parameters in Crop GIS-ABM are described in Table 5-4.

Table 5-4 Crop GIS-ABM parameters

Parameters	**Field**	**Data type**	**Description**
Time steps	MaxNumTimeStep	Double	The number of time steps specified for a model run
Neighbours' proximity effects threshold	NeighboursEffectsThreshold	Double	The maximum tolerable number of different neighbours who produce different crops to the agent as a fraction of all neighbours
Ryegrass percentage	PercentRyeGrass	Double	The ratio of agents that produce ryegrass to the total number of agents
Gross margin	GrossMarginPoppy GrossMarginPotato GrossMarginRyegrass GrossMarginHemp	Double	The growth margin of the ryegrass, poppy and potato were defined as parameters to allow the model-user to change them. Farm gross margins calculate all annual production costs and income of a particular crop on a per-hectare basis
Irrigation availability	Irrigation	Boolean	The choice between having or not having a decision rule based on Irrigation area in the region.
Quantity/ Area	Quantity	Boolean	The choice between a decision rule based on a count of different neighbours and a decision rule based on an area of different neighbours.

5.2.4 Rules and actions

An action controls the different type of functions and rules (North, Collier & Vos 2006). The actions in Crop GIS-ABM are functions and decision rule sets (e.g. agent initialisation, Farmer's decision on crop rotation) that were scheduled to run at each model time step. Crop GIS-ABM model, as an object-oriented model, has self-directed agents that may call one or a combination of actions and return their values while the model runs. Table 5-5 summarises the main actions and describes their functions in Crop GIS-ABM.

Table 5-5 Crop GIS-ABM actions

Actions	**Description**
initAgents	Call upon the agents to boot up and call other actions to initialise the agents
updateDisplay	Update and refresh the ArcMap display
writeAgents	Set the current block attribute and save the changes to the shapefile
setupBlocks	Load spatial data and set blocks and their neighbourhood
printNeighbours	Count the number of each block's neighbours and print them to console
CropArea	Count the number and calculate the area of each crop type
step	Farmer agent act at each time step based on other orders of actions
chooseQuantity	Check crop dissimilarity within the neighbourhood based on the number of neighbours and compare the tolerance threshold
chooseArea	Check crop dissimilarity based on the area of crops produced with neighbours based on the tolerance threshold
CropRotation	Check the last year crop type for rotation, find a new crop and change the current crop
GrossMargin	Calculate the gross margin of the crops (ryegrass, poppy and hemp) and choose the most profitable crop
GrossMarginIrr	Considers the gross margin of the crop by calculating the crop's suitable area plus the marginal area in the parcel
EndTimeStepUpdate	The actions are executed at the end of each time step (year) and provide a summary report

5.2.5 Schedules

A schedule in Crop GIS-ABM controls when the actions run. Farmer agents may perform actions synchronously (at each time step) or asynchronously (as regards to other agents' action or an exact time) (Johnston 2013). The scheduled actions in the Crop GIS-ABM are illustrated in Table 5-6. One time step in the model is a single year, and simulations were run for ten years. Although the default of ten years was defined in the model, the model-user can run it in various time steps.

Table 5-6 Crop GIS-ABM schedules

Actions	Schedule		
	Year (1)	Year (2, 3, 4…9)	Year (10)
initAgents	*		
writeAgents	*		
setupBlocks	*		
CropArea	*	*	*
GrossMargin	*	*	*
GrossMarginIrr	*	*	*
step	*	*	*
chooseQuantity	*	*	*
chooseArea	*	*	*
printNeighbours	*	*	*
updateDisplay	*	*	*
writeAgents	*	*	*
step	*	*	*
CropRotation	*	*	*
EndTimeStepUpdate			*

In this section, actions schedule time are discussed. The process of execution of actions in Crop GIS-ABM considers some sets of decisions to optimise the farmers' choice on crop type. The Farmer agent decides on crop type following the set of decisions such as a suitable area for a crop, gross margin, gross margin under irrigation, neighbours' proximity effect and crop rotation. The actions summarised in Figure 5-4 (see section 5.1.3) reflect the algorithms of Crop GIS-ABM. Table 5-6 illustrated that the scheduled actions in Crop GIS-ABM reflected the algorithms' steps. It implied that Crop GIS-ABM aligns the steps in the algorithms. It is also notable that the actions in Crop GIS-ABM tie in well with the important influential factors that emerged from stakeholders' insights.

5.3 Crop GIS-ABM implementation

Once Crop GIS-ABM was developed, the next step was to run it and check whether the simulation model was working and fulfilling its intention, ensuring that the computer program was adequately debugged. Error checking as a 'debugging step' (Gilbert & Troitzsch 2005) is difficult to carry out with Crop GIS-ABM due to its dependence on (pseudo) random number generators for initialising Farmer agents on the land parcel. To ensure the Crop GIS-ABM was correctly implemented, it was run multiple times with the same parameters. Further, the effects of each parameter on the model output were tested through the Sensitivity Analysis (SA) technique to determine which parameters were sensitive.

5.3.1 Initialisation

As discussed in Chapter Three, the Dorset region is a suitable case study for understanding agricultural land use change. Input data for the Crop ABM-GIS consists of GIS layers and census data. The GIS layers of the Dorset region were used in Crop GIS-ABM including crop suitability information, soil maps, slope maps, land capability maps and land use maps. These spatial data were developed by DPIPWE. The irrigation expansion districts were GIS layers provided by the Tasmanian Irrigation Co.

The most important crops, as elicited by the interview and survey findings (potato, poppy and ryegrass), were chosen for simulation. The potato was a crop highly valued among the study participants. Poppy, as a high-value crop, was also considered for the simulation because farmers are familiar with it and have cultivated it in the region for more than two decades. Ryegrass was considered as a favourite traditional crop. Ryegrass is a significant grazing enterprise in the region. The survey findings revealed that farmers' tendency to practise grazing of pasture for dairy, beef and production is higher than for other traditional crops.

The gross margin parameters for the crops (ryegrass, potato and poppy) in the Crop GIS-ABM were again adopted from DPIPWE reports (Macquarie Franklin 2012, 2018a, 2018b). The Neighbours' proximity effect threshold parameter was initialised based on suitable approaches identified in relevant literature (Ellen & Turner 1997; Sutherland et al. 2012; Vroege 2017). The Quantity parameter was initialised as 'True' and the Irrigation parameter was not initialised, as it was assumed that irrigation would not expand during the simulation. The Crop GIS model allowed the simulation to start performing when all pre-defined parameters were accepted or justified. The other pre-defined parameters initialised are summarised in Table 5-7.

Table 5-7 Parameter initialisation for Crop GIS-ABM

The parameter in Crop GIS-ABM	**Unit**	**Initialisation**	**Description**
PercentRyegrass	[0-1]	0.8	The ratio of agents that produce ryegrass to the total number of agents
PoppyGrossMargin	$	3030	Poppy gross margin
PotatoGrossMargin	$	7450	Potato gross margin
RyegrassGrossMargin	$	3295	Ryegrass gross margin
NeighboursEffectThreshold	[0-1]	0.3	The effect of neighbour's choice
MaxTimestep	Year	10	Maximum time step for simulation
Quantity	True/False	True	Crop dissimilarity within the neighbourhood
Irrigation	True/False	False	The availability of the irrigation

5.3.2 Error Checking

As noted above, Crop GIS-ABM was run several times with the same parameters for the period of ten years. The farmer agents decide the crop types. Each block is resided by a Farmer agent. The poppy, potato and ryegrass crops were placed randomly on the agricultural land. Farmer agents behave and interact with other agents based on action rules and pre-defined parameters. The outputs were recorded and compared to highlight differences between ten runs of the model.

The outcomes of the simulations were compared based on the number of farmers who choose crops (ryegrass, potato and poppy) and the areas in the regions with the same parameters. Table 5-8 illustrates the summary of the average and the Standard Deviation (SD) of each crop chosen by farmers. The simulation was rerun to check that significant errors had not occurred. The standard deviation of the percentage of each crop was less than 0.005, which indicated that there was not a significant difference between the results of the simulations during the multiple runs.

Table 5-8 Summary of the ten runs of the simulation

Component	**Average**	**Median**	**Standard Deviation**
Ryegrass%	81.7%	81.8%	0.00123
Potato%	11.3%	11.4%	0.00137
Poppy%	6.8%	6.9%	0.00098

Although the Crop GIS-ABM includes random number generators for initialisation of the farmer agents, there is a stable statistic distribution of the crops chosen by farmers in the mentioned tests. The broad implication of these ten tests is that the outputs were highly unlikely to be the result of an error in programming.

5.4 Sensitivity analysis (SA)

After using a set of test cases to check the Crop GIS-ABM was working as intended, the robustness of the Crop GIS-ABM was checked to ensure the model's behaviour represented farmers' behaviours and agricultural patterns. Sensitivity analysis (SA) as a central technique was used to test and determine which behaviour of simulations was sensitive, by a small amount, to the assumptions and the value of parameters (Gilbert & Troitzsch 2005). SA was employed in this study to determine the relative impact of several parameters on Crop GIS-ABM outputs and test the effects of each parameter on the simulation results. A local sensitivity 'one-at-a-time' approach was used to examine parameters in the model by varying each parameter by ±10% as recommended by Ten Broeke, Van Voorn and Ligtenberg (2016).

The local model parameters (e.g. ryegrass, poppy and potato gross margins, neighbours' proximity effect) were individually varied by a fixed amount (± 10%) to evaluate the local sensitivity. The results of the sensitivity analysis are illustrated in Table 5-9.

Table 5-9 Sensitivity analysis of the model parameters

Component	Parameter	Value	Change	Sensitivity outcome	
Gross Margin Ryegrass	RyeGrassGrossMargin	$3290 per ha	+10%	Ryegrass	-0.3%
				Potato	0.1%
				Poppy	3.2%
			-10%	Ryegrass	-0.3%
				Potato	1.8%
				Poppy	0.5%
Gross Margin Potato	PotatoGrossmargin	$7450 per ha	+10%	Ryegrass	0.3%
				Potato	-1.0%
				Poppy	-2.3%
			-10%	Ryegrass	-0.7%
				Potato	2.9%
				Poppy	4.1%
Gross Margin Poppy	PoppyGrossMargin	$3030 per ha	+10%	Ryegrass	0.0%
				Potato	-2.1%
				Poppy	3.2%
			-10%	Ryegrass	0.2%
				Potato	-1.0%
				Poppy	-0.5%
Percent Ryegrass	PercentRyeGrass	0.8	+10%	Ryegrass	0.3%
				Potato	-1.5%
				Poppy	-0.5%
			-10%	Ryegrass	-0.5%
				Potato	2.3%
				Poppy	2.3%
Neighbours' proximity effect	NeighboursEffectThreshold	0.3	10%	Ryegrass	-0.2%
				Potato	-1.0%
				Poppy	4.1%
			-10%	Ryegrass	0.1%
				Potato	1.2%
				Poppy	-3.2%

Some parameters (e.g. Irrigation and Quantity) cannot be altered by 10%, as they are Boolean (True/False), so these parameters were tested under conditions suitable for Boolean parameters. For example, the Quantity parameter was set to False, but on the next run it was set to True, as a method for checking the robustness of the model based on a non-quantitative parameter. Table 5-10 demonstrates the sensitivity outcomes of simulation under Irrigation and Quantity parameters.

Table 5-10 sensitivity analysis of the model parameters

Component	Parameter	Value	Change	Sensitivity outcome	
Quantity	quantity	True/False	True	Ryegrass	0.2%
				Potato	-3.2%
				Poppy	3.2%
Irrigation	irrigation	True/False	True	Ryegrass	-1.7%
				Potato	-2.7%
				Poppy	21%

The main conclusion that can be drawn from Table 5-9 is that the sensitivity to perturbations of the crops sown was relatively small in most input parameters, with poppies generally being highest and ryegrass generally lowest. The data in Table 5-10 indicates that decision-making on poppies is highly sensitive to whether or not irrigation is present. Irrigation availability was assumed to improve marginal land to suitable land for crop production. Most areas in the Dorset region are only marginally suitable for poppy. If irrigation is available in the region, the farmer agents can choose to produce poppy. Therefore, poppy is more sensitive to irrigation than ryegrass and potato.

The outcome of the sensitivity analysis is shown in Figure 5-6. The comparison between the proportional change in parameters with variable (ryegrass, poppy and potato crops) indicates that the Crop GIS-ABM is reasonably robust to local change in most parameters. The gross margin parameters, neighbours' proximity effect and ryegrass percentage, are relatively insensitive parameters. Irrigation availability is a highly sensitive parameter that represents around 21% change in the number of lands becoming available for poppy crop production. This indicates a high preference for poppies in favour of irrigation availability in the model.

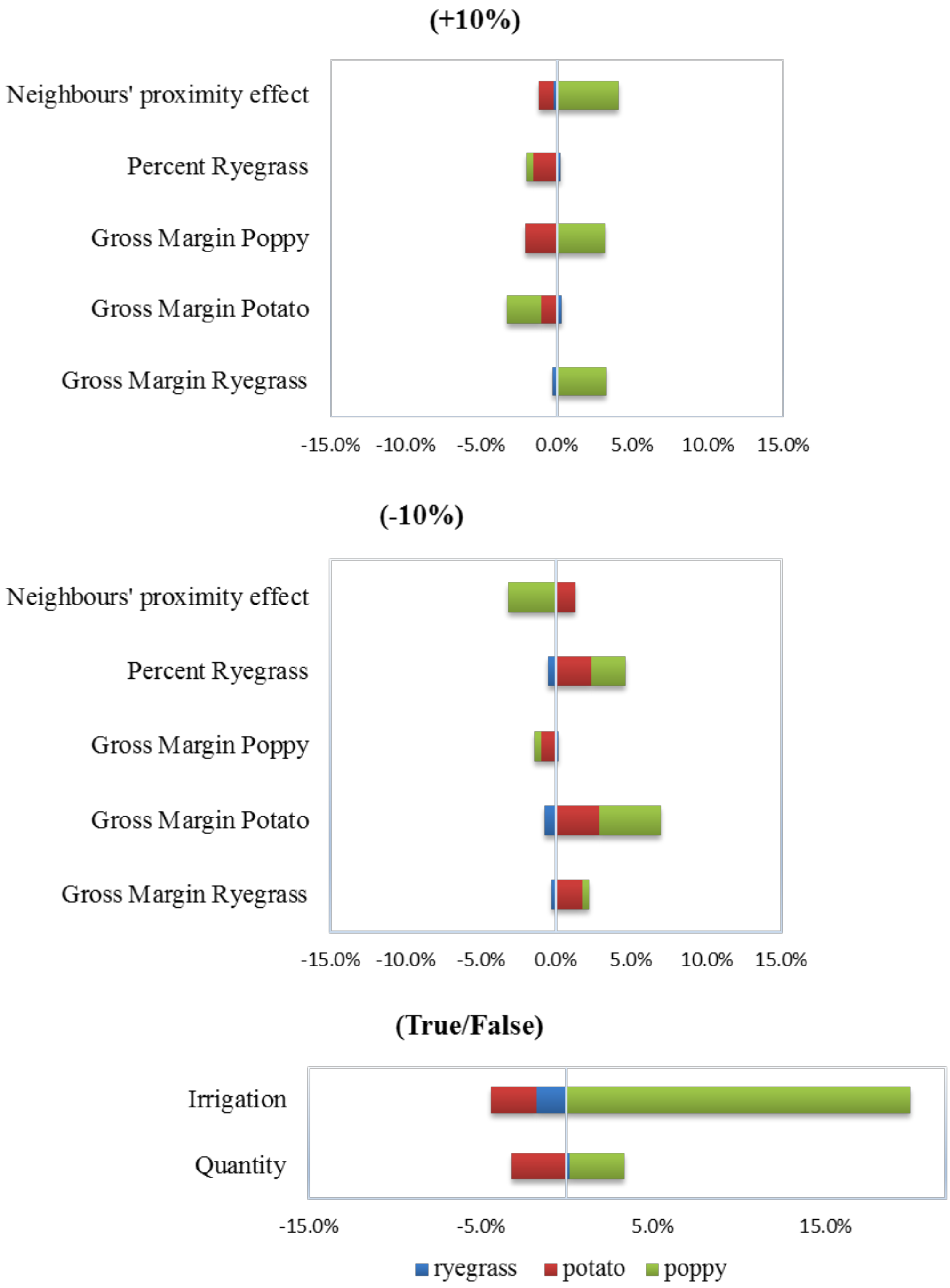


Figure 5-6 Sensitivity analysis of the Crop GIS-ABM parameters

5.5 Summarising the second stage: the development of the simulation model (Crop GIS-ABM)

Crop GIS-ABM is a simulation model designed and developed in this study with the objective of providing decision-makers with the means to run scenarios on the impact of land use change in agricultural landscapes. Specifically, Crop GIS-ABM is seeking to address a gap in land use planning, which for the most part fails to take into account the cumulative effect of the many decisions that farmers make in regards to the utilisation of land and investment in new technologies and new and different crops and production. Chapters Four and Five discussed the process of developing the conceptual model of farmers' decisions and the design process of the Crop GIS-ABM simulation model.

The second research question (Q2) of this study was focused on developing a simulation model by integrating the important influential factors. In the second stage, the most important influential factors that emerged from stakeholders' insights were transferred to algorithms. The algorithms' steps were aligned with the conceptual model of farmers' decisions. The spatial data and the algorithms were linked through Agent Analyst software and the resulting simulation model named Crop GIS-ABM by the researcher. Parameter sensitivity was then checked through sensitivity analysis. The second stage demonstrated that using a simulation model facilitated the integration of qualitative and quantitative data through algorithms and the Crop GIS-ABM is a simulation model that represents the farmers' decision model.

The result of the first stage is a conceptual model of farmers' decisions based on the most important economic, social and environmental influential factors. The conceptual model was programmed in the Crop GIS-ABM for investigation of the relationship of micro-scale and macro-scale decisions on agricultural land use.These two stages have demonstrated that it is possible to build a simulation model that reflects stakeholders' insights and that a multistage design research method facilitates the process of developing Crop GIS-ABM. In the next Chapter, Crop GIS-ABM simulates a set of agricultural scenarios and the simulation outcomes are analysed.

Chapter 6: Scenario Analysis (Stage 3)

6.1 Introduction

A key goal of this research is to demonstrate how the integration of stakeholder insights with a spatial ABM can provide a better understanding of how farmers' behaviours influence the dynamic emergence of agricultural land use patterns. The Crop ABM-GIS model was developed, and the internal validity of the model was tested. In Stage 3 (Chapter 6) the third research question (below) is addressed with testing of the simulation model through scenario generation and analysis:

- *(Q3) Could farmers' decisions and behaviours on adoption of new alternative crops be simulated to answer: To what extent does the irrigation expansion promote the diffusion of alternative crops in the region? How does farmers' crop choice alter the regional land use and the crop patterns over time?*

Three scenarios are developed, each informed by the third research question, and seeking to explore farmers' choices on alternative crops/livestock in relation to irrigation expansion in the Dorset region. These scenarios reflect both macro-scale decisions and the farmers' choices (micro-scale decisions) related to agricultural land use at the regional scale over time.

Crop GIS-ABM (spatial ABM) simulates a set of agricultural scenarios and visualises agricultural land use patterns over time. Such an approach provides an indication of how farmers' choices and behaviours might change under different agricultural policy and scenarios, and what the impacts might be. The outcomes of the simulations are analysed to investigate how farmers make decisions. The emerged spatial patterns are compared with stakeholders' sketched maps to explore the degree to which the simulated agricultural crop patterns in the region match with stakeholders' insight about the future landscape regarding alternative crops/livestock and irrigation expansion scenarios. In effect this Chapter 'tests' the Crop GIS-ABM's potential for simulating agricultural scenarios.

6.2 Simulation scenarios

As described in previous chapters, this study is grounded in geodesign methodology (Steinitz 2012). A key feature of geodesign is the utilisation of design thinking, which enables the development of possible scenarios to outline different hypothetical futures, in this case for agricultural land use in the Dorset region as a case study. The aim of scenario analysis is to assist decision-makers to be able to decide more deliberatively (Parker, AM et al. 2015) through better estimation of uncertainty (Wright, V 2011; Wright, G, Bradfield & Cairns 2013) and explore the complex effects of policy – in this case irrigation expansion. Crop GIS-ABM facilitated scenario analysis in this study. Crop GIS-ABM was used to simulate 'change' scenarios under different experimental conditions to not only achieve a better understanding of the farmer agent's decisions, interactions and behaviours but also explore and visualise the emergence of land use and crop patterns in Dorset as the case study region.

Three scenarios addressed a series of possibilities that might emerge because of a different set of assumptions about the consequences of agricultural policy (e.g. irrigation expansion) or shifts and fluctuations in commodity prices and farmers' choices and behaviour at a regional scale. Table 6-1 summarises the scenarios. These scenarios describe the uncertainty of the adoption of new alternative crops/livestock (e.g. hemp) by considering different factors and exploring possible agricultural futures. Further, simulation of three scenarios in Crop GIS-ABM accommodates the visualisation of several possible futures for agricultural land within the same case study.

Table 6-1 Simulation scenarios

Scenarios	Purpose	Description
Scenario 1 (S1)	Adoption of new alternative crop/ livestock	In the next ten years, if a new alternative crop is introduced to farmers in the Dorset region, half of the farmers will produce alternative crops/livestock.
Scenario 2 (S2)	Irrigation expansion and its impacts on the adoption of the new alternative crops/livestock.	If the irrigation expands in the Dorset region, the percentage of farmers who produce alternative crops/livestock will increase, and the adoption rate of alternative crops/livestock will increase.
Scenario 3 (S3)	Potential effects of agricultural commodity price on agricultural land use change	If the price of milk increases, the percentage of farmers who produce alternative crops/livestock and the aggregate rate of alternative crops/livestock adoption will decrease in the Dorset region.

<u>Scenario 1 (S1)</u>

The first scenario investigates how farmers' decisions on adoption of new alternative crops/livestock change agricultural crop patterns in the regions. This scenario is conducted at micro-scale. It specifically centres on farm scale decisions and the farmers' decisions on crop type such as the decision regarding the adoption of new and potentially higher value crops. The Crop GIS-ABM simulates the first scenario and the outcome of the simulation helps to understand the process of adoption of the new alternative crop (e.g. hemp) and considers the spatial impacts of farmers' decisions on agricultural land use patterns.

<u>Scenario 2 (S2)</u>

The second scenario considers how farmers' decisions and behaviour might change in response to agricultural policy such as irrigation expansion in the region. The expansion of irrigation was considered for scenario analysis as this is a critical change with widespread potential impacts at the regional scale. In the new irrigation expansion scenario, which is a macro-scale scenario, the Crop GIS-ABM simulates the irrigation expansion in order to explore how crop patterns might change and the cumulative impacts on land use.

Scenario 3 (S3)

The third scenario provides an example of the possible effects of changes in agricultural commodity prices on crop patterns in the context of farmers' decisions and behaviours over the next ten years. The third scenario is also macro-scale because it includes macroeconomic variables, not 'controlled' by farmers. International and domestic market demands play an important role in determining farm product prices (Tomek & Kaiser 2014). The Crop GIS-ABM, therefore, simulates the commodity price change to explore the effect of price changes on farmers' decision and behaviours and subsequent effect on land use and land use change.

These scenarios were implemented in Crop GIS-ABM, and the outcomes of the simulations were analysed.

6.2.1 Scenario 1 (S1)

The purpose of simulating a micro-level scenario is to explore farmers' behaviours in regards to the adoption of a new alternative crop in comparison with popular traditional crops. As was described in Chapter Four, analysis of the survey data revealed that most of the participants were open to the possibility of introducing an alternative crop and hemp was seen as a good example of a new alternative crop in and for the Dorset region. Therefore, hemp was selected as a new alternative crop to be simulated by Crop GIS-ABM.

In Scenario 1 the adoption or uptake of the alternative crop (hemp) was explored by comparing the area under hemp production after ten years with that of some common traditional crops such as ryegrass and poppy – crops that had been produced for much longer in the region. The adoption of hemp in the region was visualised by utilising an ArcGIS display function. The following sections outline how the simulation was set up using the Crop GIS-ABM as developed and discussed in Chapters Four and Five.

Initialisation

Input data for the Crop ABM-GIS consists of GIS layers and census data. Based on the study survey findings, hemp (and the new alternative) and poppy and ryegrass[5] (as traditional productive performing crops) were chosen for the simulation. The interview respondents were largely in agreement that hemp was an appropriate new alternative crop. By way of additional support it is noted that hemp is considered to be a profitable cropping alternative for farmers in Tasmania (Hemp Association of Tasmania 2018). Poppy is well established in Tasmania as a high-value crop and was therefore considered as appropriate for the simulation because farmers are familiar with it. Ryegrass is a significant grazing enterprise in the Dorset region and for many a favourite traditional crop. The survey findings also revealed that, in the Dorset region, there was a well-established practice of growing ryegrass pasture for dairy, beef and sheep production and indeed it was rated more highly by some than potatoes (historically traditional and important) and poppy (albeit a well-established and high value crop). For these reasons hemp, ryegrass and poppy were the crops selected for these simulation scenarios.

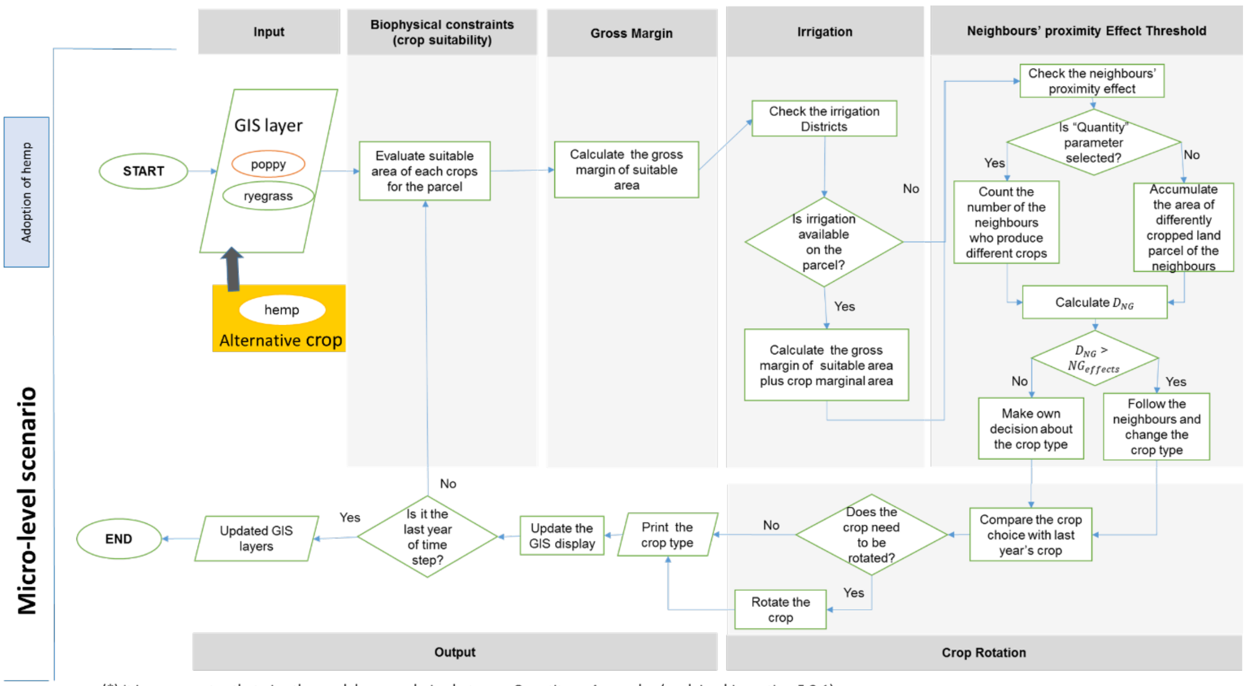
The adoption of innovation rate (InnovationAdapotorsRatio parameter) measure used for the Crop ABM-GIS simulation is the percentage of farmers who might be early adopters of hemp (i.e. an innovator). As explained in Chapter Two, around 2.5% of the members of a social system are innovators (Rogers 2002). Therefore, the adoption rate of hemp was initialised at 2.5% of the farmers in the Dorset region. The other parameters were initialised following the settings developed in Chapter Four. The parameters used for testing the micro-scale scenario are summarised in Table 6-2.

[5] A ‘ryegrass crop’ is grown for ‘ryegrass pastures’, which are intended for grazing.

Table 6-2 Parameter initialisation – alternative crop scenario

Parameter	Unit	Initialisation	Description
InnovationAdoptersRatio	%	2.5	Adoption rate
PoppyGrossMargin	$	3030	Poppy gross margin
HempGrossMargin	$	1290	Hemp gross margin
RyegrassGrossMargin	$	3295	Ryegrass gross margin
NeighboursEffectThreshold	[0-1]	0.3	The effect of neighbour's choice
MaxTimestep	Year	10	Maximum time step for simulation
Quantity	True/False	True	Crop dissimilarity within the neighbourhood
Irrigation	True/False	False	The availability of the irrigation

As was described in the previous Chapter, each block is occupied by a generic agent (Farmer) who makes decisions based on action rules and defined parameters. These rules and parameters were discussed in Chapter Four. To implement the simulation model hemp as a new alternative crop, along with poppy and ryegrass, were placed randomly on the agricultural land in the Dorset region. Figure 6-1 outlines the flowchart adopted for the Crop GIS-ABM and the farmers' decision steps regarding adoption of hemp.



(*) It is a parameter that give the model-user a choice between Quantity or Area rules (explained in section 5.3.1)
(**) It is an equation that calculates a ratio of the differently cropped neighbour parcels to the total neighbours (explained in section 5.3.1)
(***) It is Neighbours' proximity Effects Threshold (explained in section 5.3.1)

Figure 6-1 Farmers' decision flowchart for hemp adoption

During the simulation, spatial data were collected about parcels, crop suitability, and land capability from the GIS layers. In deciding on a given crop type, each ‘Farmer agent’ considered the tendency to produce a new alternative crop along with other factors such as gross margin, irrigation availability, neighbours’ proximity and crop rotation. The simulation length was set to ten years (as per the Crop GIS-ABM model). The model stopped at the end of the time step (the time step was yearly), and the regional pattern of crops in the Dorset region was represented in the ArcGIS display.

Scenario analysis (S1): adoption of hemp

The scenario of hemp adoption was used to explore how farmers make decisions on adoption of new alternative crops and what happens to land use in response to these decisions. Figure 6-2 illustrates the simulation results for the adoption of hemp by farmers over ten years in the Dorset region. Simulation outputs were analysed based on two variables, namely:

- The number of land parcels under hemp production each year,
- The accumulated number of hemp adopters (cumulative number of farmers who produced hemp over ten years).

As can be seen from the graph, there is an upward trend for hemp adoption in the region with an increase in the number of farmers who produce hemp from 6 to 78 farmers in the first five years. In the second five years, the cumulative number of hemp adopters increased at a slower rate to 98 farmers. The outcomes of the simulation indicate that an overall number of 265 farmer agents decided to produce hemp during the ten years of simulation, i.e., 18% of the total farmers in the regions are likely to produce hemp at least once after its introduction in the Dorset region (during the ten years). Analysis of simulation outcomes indicates the possible rate of hemp adoption in the Dorset region is around 18% during ten years of simulation.

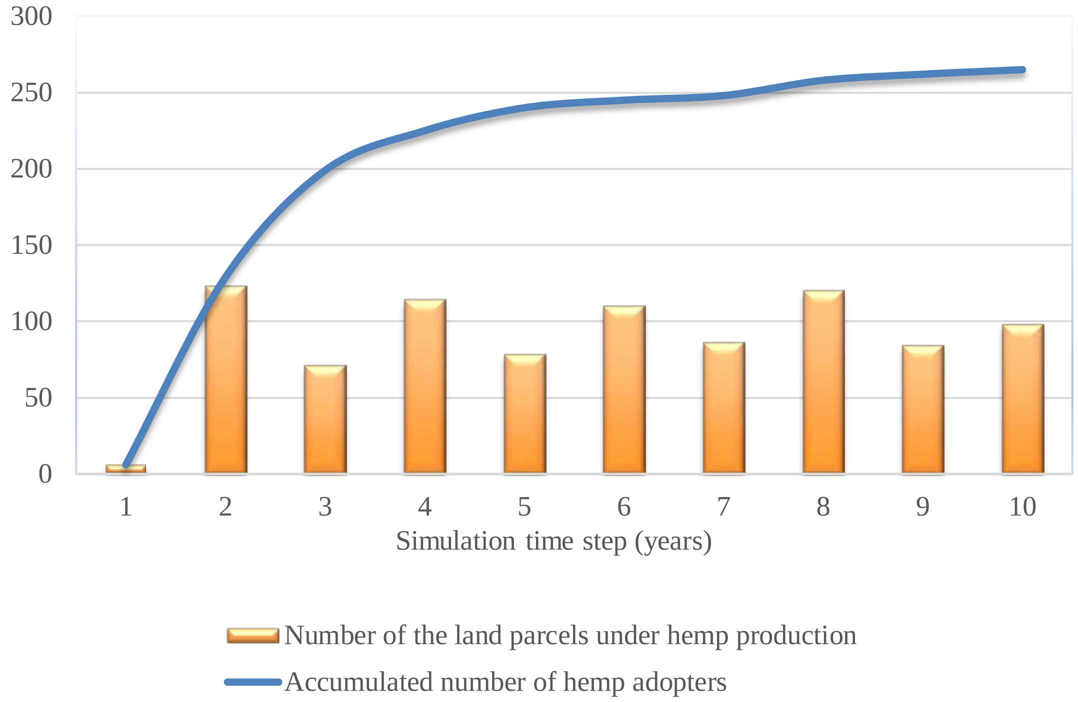


Figure 6-2 Diffusion of hemp in the Dorset region

Despite the upward trend in hemp adoption, the number of land parcels under hemp production fluctuated gradually during the ten years of simulation. Based on the simulation results, an average number of 86 land parcels each year produced hemp for ten years. For example, around 123 farm land parcels produced hemp during the second year of the simulation, which was the highest number of hemp adoption. In the third year, this number dropped to 71 farmers, increased to 114 farm land parcels in year four, and decreased to 78 farm land parcels in year-five. There are two possible reasons behind the fluctuation of the number land parcels under hemp production.

Firstly, biophysical restrictions such as the crop suitability of the farmland and crop rotation are the most important reasons for fluctuation in the number of land parcels that produced hemp during the ten years of simulation in the Dorset region. The Crop GIS-ABM simulation includes these spatial and biophysical factors. Thus, for example, if Farmer (A) chose hemp in the second year, because of crop rotation he/she cannot produce hemp in the third year. Similarly, another farmer, Farmer (B), might be interested in a new crop such as hemp because it is a profitable crop, and the neighbours and the social network support this decision, but the biophysical characteristics of the land parcels might not be suitable for hemp. As a result, there is fluctuation in the number of land parcels that produced hemp because of crop suitability and rotation.

Secondly, the complexity and nonlinearity of the farmers' decision model are also reasons for the fluctuation in land parcels that produced hemp over the ten-year time frame. If the neighbours of Farmer (C) choose to produce hemp, he/she is more likely to choose hemp in the coming years because of the neighbours' proximity effects. As described in Chapter Two, farmers' adoption decisions are not driven solely by their goals and personality, as occurs in a customer innovation-decision model. On the other hand, the farmers' decision-making process is not completely like an organisation adoption model based on formal structures and procedure for investing in 'new technology'. The farmers' decision model is a function of not only their tendency to grow traditional crops and their social network but also the costs and profits of farm products, amongst other factors. Therefore, the simulation of hemp is non-linear because the farmers' decision involves several factors.

Spatial Analysis (S1): hemp adoption scenario

The spatial diffusion of hemp in the Dorset region was analysed through the simulated maps. Figure 6-3 shows a spatial pattern for hemp adoption in the Dorset region. As can be seen in the map, the number of land parcels that grew hemp was clustered in several districts (Bridport, Ringarooma, Scottsdale, North Scottsdale and Ledgerwood). The average size of the farms that produced hemp was around 113ha in the Dorset region in this scenario.

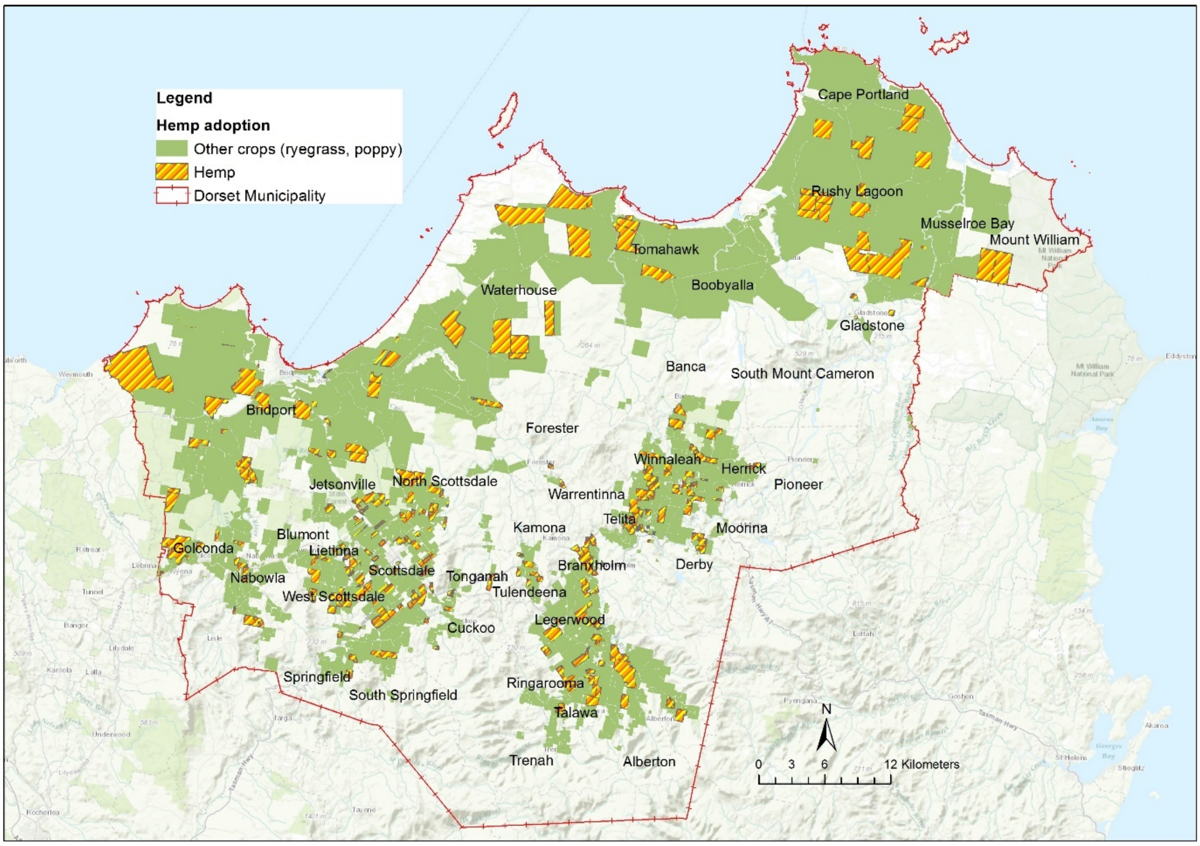


Figure 6-3 Adoption of hemp in the Dorset region

Interestingly, in the interviews the participants indicated that the size of the farm was not a significant factor for decision-making on alternative crops as long as the overall profit of adoption of the new alternative crop (e.g. hemp) could be achieved. The spatial analysis of the simulation outcomes and visualisation of the data supports the participants' insights about land parcels and, by implication, farm size. As Figure 6-3 shows, while the average size of land parcels that produced hemp was 113ha, there were land parcels in the Ledgerwood, Ringarooma, Scottsdale, North Scottsdale districts of the region smaller than 113ha that produced hemp. The average size of the land parcels in the Legerwood district that produced hemp was around 62 ha and 51ha in the Ringarooma district. The result of the simulation shows that even the farmers who have small land parcels are likely to be hemp adopters.

The Crop GIS-ABM allowed investigation of the complexity of crop choice by farmers. For example, ryegrass pastures are a favourite crop choice among farmers and farmers might tend to intensify ryegrass for dairy/livestock or poppy rather than select a new alternative crop. That said, ryegrass pasture and poppy remain a more certain crop. This may change as the legislation pertaining to regulatory requirements conditions for growing hemp changes.

6.2.2 Scenario 2 (S2)

It is proposed that the Crop ABM-GIS can also be used to investigate the effects that different agricultural policies may have on agricultural land use and land use planning. In this study, the expansion of irrigation was considered for scenario analysis as this is a critical change with widespread potential impacts on agricultural land use. The decision to expand irrigation in the region is not a decision that is made by farmers albeit it potentially benefits them, and they may well encourage their interest groups to lobby on their behalf. Nevertheless, it is instead a macro-scale decision that affects farmers' decisions on crop choice and has impacts on land use.

In the first scenario, farmers' behaviour and decision-making at the micro scale in regards to hemp adoption were simulated and the emerging patterns of hemp adoption were analysed. In the second scenario, the effects of irrigation policy on agricultural land use change were examined in the context of the adoption of an alternative crops/livestock in the Dorset region. Specifically, the irrigation expansion scenario investigates (1) how farmers' behaviours and decisions on adoption of hemp might change if irrigation expands in the Dorset region and (2) what crop patterns might emerge as a consequence.

The assumption is that with access to irrigation, farmers can not only expand the area under crop production but also try out other new crops. Thus, the assumption proposes (1) an increase in the land area available (under any crop) and (2) an increase in types of new crops that may require more water (which is now available). This scenario proposes therefore that if a high-value crop covers the cost of irrigation investment, adoption of new alternative crops under irrigation will increase.

Initialisation

Based on the interview findings, farmers indicated that if the irrigation is available they could increase their yields and intensify their crop products by trying new crops. That is, participants indicated that if the irrigation expanded, they would contemplate not only investing in purchasing more water (and infrastructure) to intensify their traditional crop (e.g. ryegrass) but also consider adoption of a high-value new alternative crop (e.g. hemp) as a solution to cover the increased water costs. The cumulative number of farmers who chose a new alternative crop compared to the total number of farmers is a factor that can show the tendency of farmers in the region to adopt new alternative crop when irrigation expansion was a viable option.

In the Crop GIS-ABM, if the land parcel is located inside the identified irrigation districts, the Farmer agent is in a position to invest in irrigation to intensify their cropping by converting marginal areas to suitable areas. By expanding cropping into the marginally suitable areas, farmers could plant more of the crop. Further, if the land parcel is inside the identified irrigation districts, a Farmer agent can consider all the crop options (traditional or new alternatives) and calculate the gross margin by considering suitable and marginal areas. Considering marginal and suitable areas (because of irrigation expansion) is the difference between the first scenario and the second scenario.

Input for the Crop ABM-GIS modelling of this scenario consists of data from the State irrigation company’s map along with DPIPWE GIS layers and census data. Figure 6-4 shows the current and proposed irrigation districts based on the State irrigation company’s map for the Dorset region. Current and proposed districts were initialised as irrigation areas in the simulation.

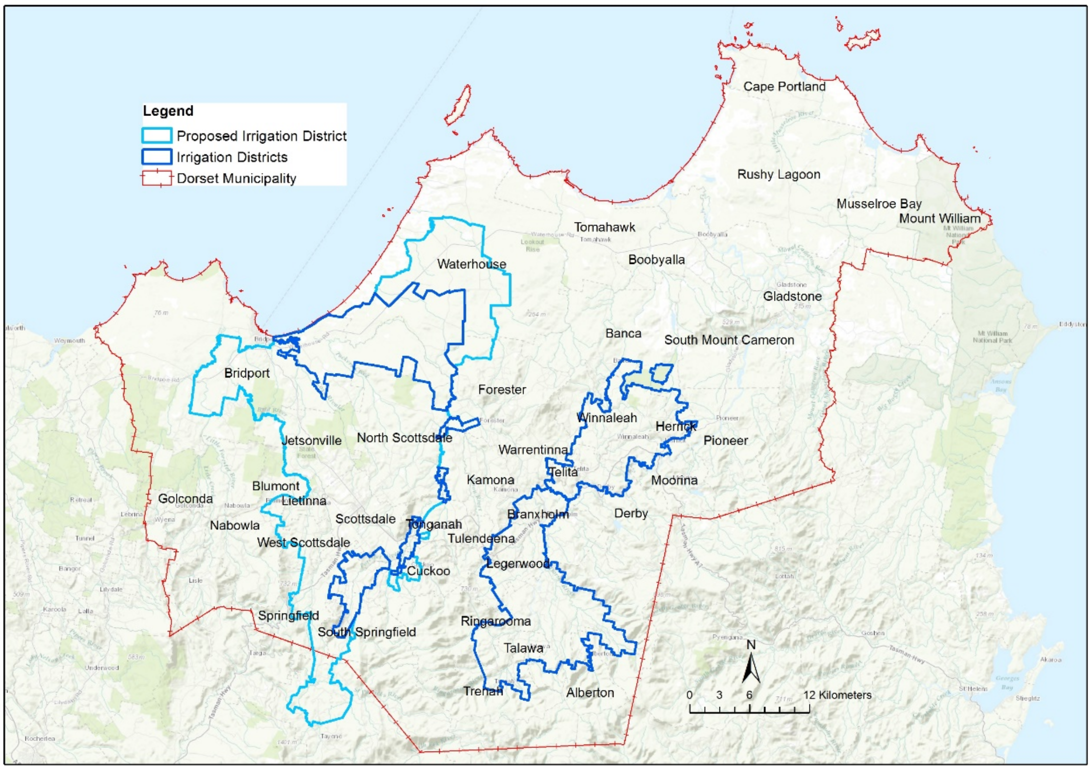


Figure 6-4 Current and proposed irrigation areas in the Dorset region

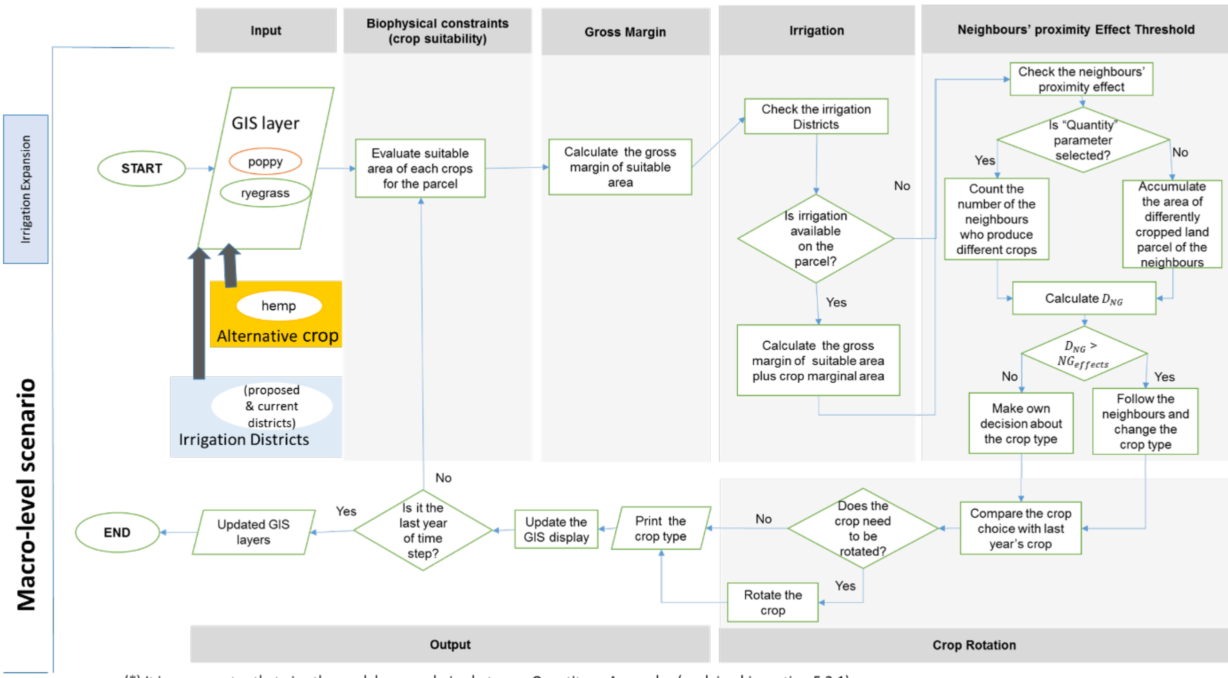
As described in Chapter Four, however, three-phase electrical power is also a factor that affects farmers' decisions on the adoption of irrigation. Unfortunately, three-phase electricity data and maps for the Dorset region were not available for this research. Therefore, it is assumed in the Crop GIS-ABM modelling that three-phase electrical power is available for Farmer agents in the identified irrigation districts. Thus, for the purposes of initialisation, if a land parcel is inside the current and proposed irrigation districts, then the Farmer agent has access to irrigation and three-phase electrical power. Therefore, the Farmer agent in identified irrigation districts can choose to invest in irrigation and subsequently consider the intensification of traditional crops (e.g. ryegrass) and/or the adoption of a new alternative crop (e.g. hemp).

The Crop ABM-GIS model parameters for testing the scenarios on irrigation expansion are summarised in Table 6-3. The adoption rate of hemp is the percentage of farmers who are early adopters of hemp (innovator). Similar to the previous scenario, the number of farmers who might adopt an irrigation scheme was initialised as 2.5% of the total farmers. The gross margin was initialised based on relevant Tasmanian State Government reports on commodity prices (Macquarie Franklin 2012, 2018a, 2018b, 2018c). Other predefined parameters including neighbours' proximity effect (0.3) and model time steps (ten years) were initialised for the simulation.

Table 6-3 Parameter initialisation – adoption of alternative crop under irrigation expansion

Parameter	**Unit**	**Initialisation**	**Description**
InnovationAdoptersRatio	%	2.5	Adoption rate
PoppyGrossMargin	$	3030	Poppy gross margin
HempGrossMargin	$	1290	Hemp gross margin
RyegrassGrossMargin	$	3295	Ryegrass gross margin
NeighboursEffectThreshold	[0-1]	0.3	The effect of neighbour's choice
MaxTimestep	Year	10	Maximum time step for simulation
Quantity	True/False	True	Crop dissimilarity within the neighbourhood
Irrigation	True/False	True	The availability of irrigation

Figure 6-5 shows the flowchart of the decision-making process under irrigation expansion for simulating the macro-level scenario.



(*) It is a parameter that give the model-user a choice between Quantity or Area rules (explained in section 5.3.1)
(**) It is an equation that calculates a ratio of the differently cropped neighbour parcels to the total neighbours (explained in section 5.3.1)
(***) It is Neighbours' proximity Effects Threshold (explained in section 5.3.1)

Figure 6-5 Decision flowchart for irrigation expansion

As the flowchart shows, hemp, poppy and ryegrass are placed randomly on the agricultural land in the Dorset region. The gross margin was computed based on the suitability area of each crop. As it was assumed that irrigation was accessible for all farmers in current and proposed districts, farmers had a choice of producing either or both traditional and alternative crops. Farmer agents also considered two other factors – the neighbours' proximity effect and crop rotation.

In the simulation, Farmer agents compared three farm enterprises per unit of land (i.e. per hectare) including ryegrass for dairy (existing and traditional), poppy (high-value crop) and hemp (new alternative crop) to choose the crop type for their land parcels. The simulation continued for ten years. The model stopped at the end of the time step, and the regional pattern of crops in the Dorset region with irrigation was visualised in the ArcGIS display.

Scenario analysis (S2): irrigation expansion scenario

The scenario of irrigation expansion investigates resultant land use patterns if irrigation expands in the Dorset region in the context of how many farmers will adopt a high-value new alternative crop, e.g. hemp, instead of a traditional crop.

Figure 6-6 illustrates the simulation result of the adoption of hemp by farmers by areas under irrigation expansion in the Dorset region for ten years. As the bar chart demonstrates, there is a fluctuation in the number of land parcels under hemp production during the ten years of simulation. The average number of farm land parcels under hemp production is around 76 parcels for ten years. Despite the fluctuation of parcels under hemp production, there is an upward trend for hemp adoption in the region. Further, the graph shows that there is an upward trend in the number of farmers who adopted hemp, from 6 to 192 farmers in the first five years and thereafter increasing slightly to 211 farmers in the second five years. The simulation results indicated that 14% of the total farmers are more likely to produce hemp under irrigation expansion at least once after hemp has been introduced in the Dorset region (i.e. during the ten years).

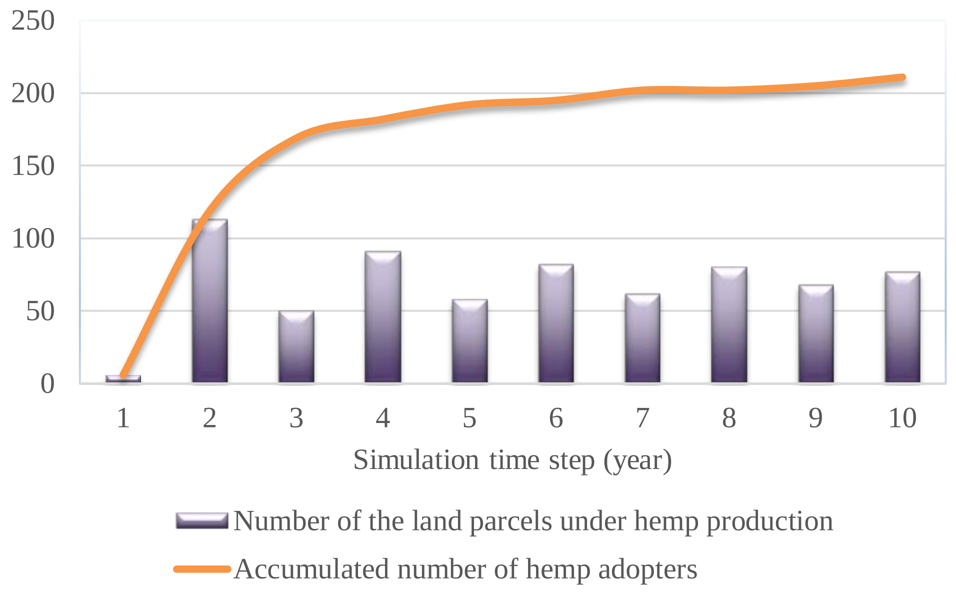


Figure 6-6 Diffusion of hemp under irrigation expansion in the Dorset region

The simulated scenario provides a picture to better understand the uptake and impact of hemp adoption. One measure, for example, is to look at the ratio of farmers who choose to produce hemp under irrigation expansion compared with farmers who select and adopt hemp without the irrigation. Similarly, the ratio of the cumulative number of hemp adopters to total farmers shows the tendency of farmers in the region to adopt hemp under irrigation expansion in comparison with the adoption of hemp without irrigation expansion.

The first scenario investigated hemp adoption without considering irrigation, while this second scenario examines the adoption of the new alternative crop (hemp) under irrigation expansion. The results of the simulations with and without irrigation expansion can also be compared and are illustrated in Figure 6-7.

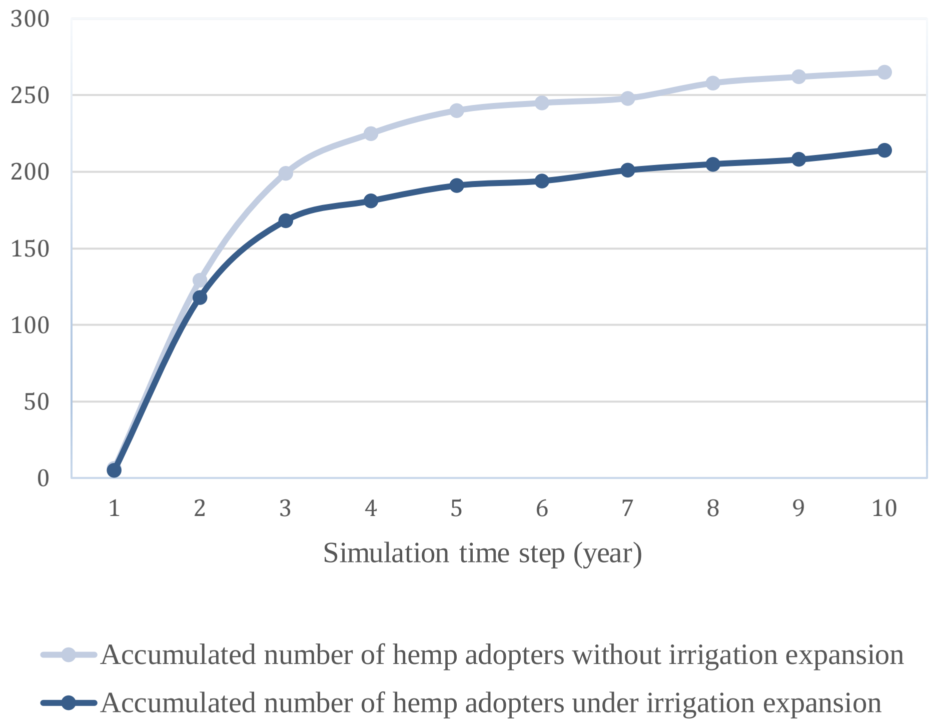


Figure 6-7 Diffusion of hemp with and without irrigation expansion in the Dorset region

Interestingly, the simulation data shows that the number of farmers who adopted hemp under irrigation expansion was less than the number of hemp adopters without expansion of irrigation during the ten years of simulation. The accumulated number of hemp adopters under irrigation was around 214 (14% of total farmers) and those who adopted hemp without irrigation was around 265 (18% of total farmers). Figure 6-7 shows that adoption of hemp decreased under irrigation expansion scenarios in the Dorset region.

The simulation data provokes the question as to why this might be. A key point made throughout the study is that farmers' decisions on crop selection, and more particularly the adoption of new alternative options (such as hemp adoption) in the context of planned irrigation expansion, is complex. The simulation data points to several practical possibilities as to what occurred. The decrease of the hemp adoption rate might be for different reasons. Firstly, the popularity of ryegrass and of the high value poppy crop influences farmers' decisions to invest in irrigation to intensify the crops that they have produced for years and that have generated sustained high-value return. Secondly, the biophysical conditions, especially the area of marginal lands per land parcel, also play an essential role in choosing the crops.

However, as the aggregate rate of hemp adoption with the introduction of irrigation was less than that without irrigation availability for ten years, the plausibility of the second scenario is undermined, and not supported, when the results of the simulations are compared. In other words, if irrigation expands in the Dorset region, farmers might well intensify the popular and more certain and high value crops such as ryegrass and poppy instead of producing the new alternative crop.

Potentially, the data provided by the simulation extends the information or tools at a farmer's disposal to make better informed choices. With this kind of information farmers can compare different crops by secure water consumption and select the crop (traditional or new alternative crop) that is more profitable than other crops.

Spatial analysis (S2): irrigation expansion scenario

The spatial diffusion of hemp in the Dorset region under irrigation expansion was analysed through simulated maps. Figure 6-8 shows the spatial pattern of hemp adoption in the Dorset region. As can be seen in the map, there is uptake of hemp production across the region and the number of land parcels that grew hemp under irrigation expansion centred in several districts (Winnaleah, Scottsdale, Bridport, Jetsonville, and North Scottsdale) in the region during the ten years of simulation. The average size of the farm that produced hemp had around 114ha under irrigation, and one district (Bridport) produced more hemp than other districts under irrigation expansion (27% of the total area under hemp production) in the region during the ten years of simulation.

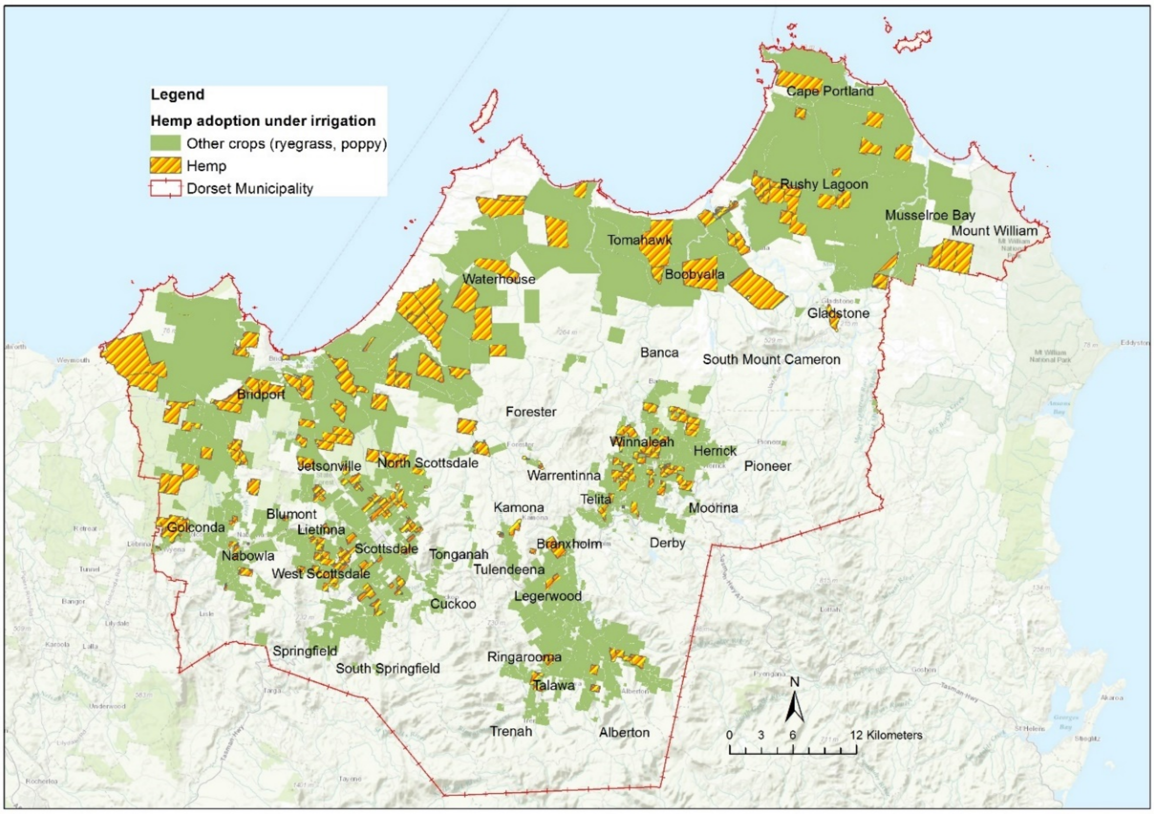


Figure 6-8 Adoptions of hemp under irrigation expansion in the Dorset region

That said, the number of hemp adopters in the under-irrigation-expansion scenario decreased in the region in comparison with the no-irrigation scenario (Scenario 1). Equally, the pattern of hemp adoption under irrigation expansion also changed, especially in certain districts or spatial areas (e.g. Winnaleah, Jetsonville). The simulation also suggests that the average size of farm land under hemp production increased slightly. These spatial changes under irrigation expansion can be explained by looking more closely at policy assumptions and an investment business case where irrigation availability was assumed to improve marginally suitable land to suitable land for crop production.

The suitability of land for particular crops (in this study hemp, ryegrass and poppy) plays a significant role in farmers' adoption decisions. Figure 6-9, 6-10 and 6-11 illustrate this relationship. The figures map areas suitable for hemp, poppy and ryegrass production in the Dorset region. The DPIWE data shows that much of the Dorset region is only marginally suitable for poppy, but most of the areas in the region are suitable for ryegrass and hemp production. Thus, if the availability of, and accessibility to irrigation increases in the region, the Farmer agents can potentially choose to access and adopt irrigation to intensify ryegrass and poppy production in their land parcels rather than choosing to grow a new alternative crop.

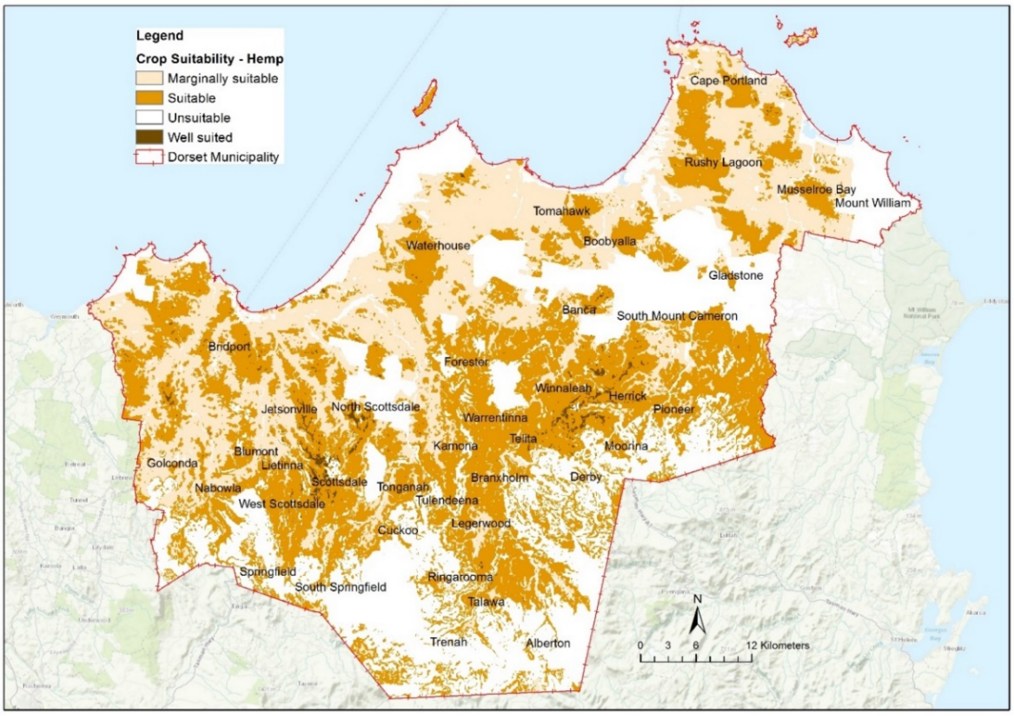


Figure 6-9 Crop suitability for hemp

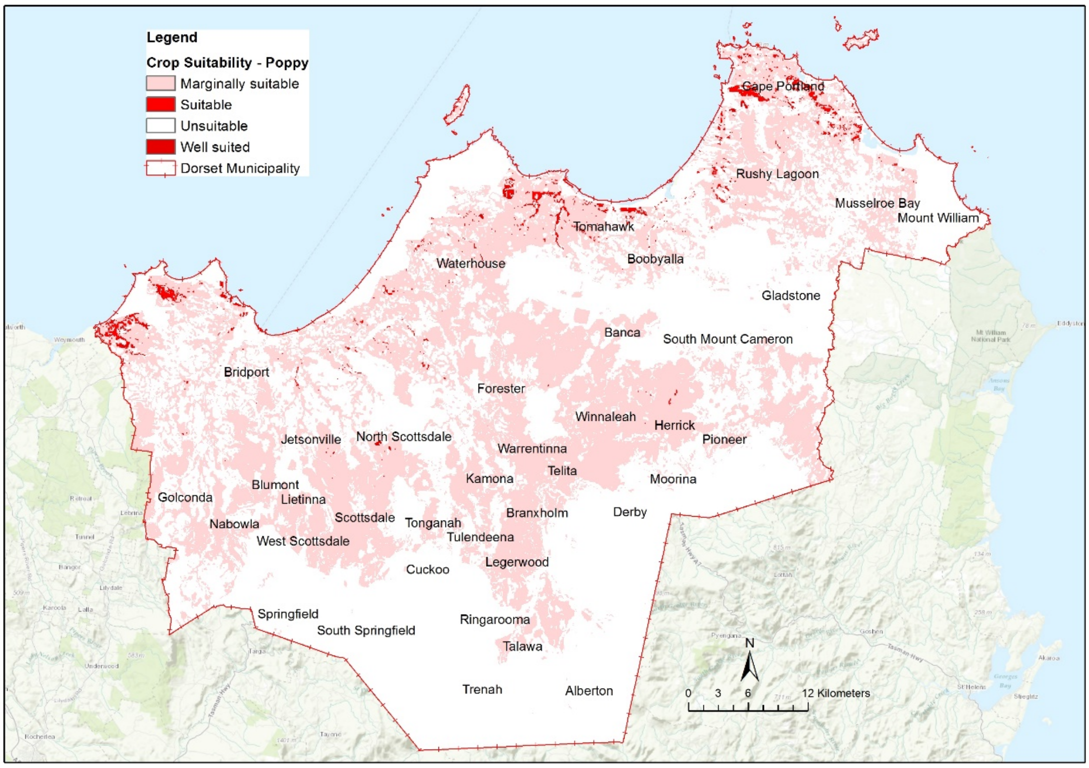


Figure 6-10 Crop suitability for poppy

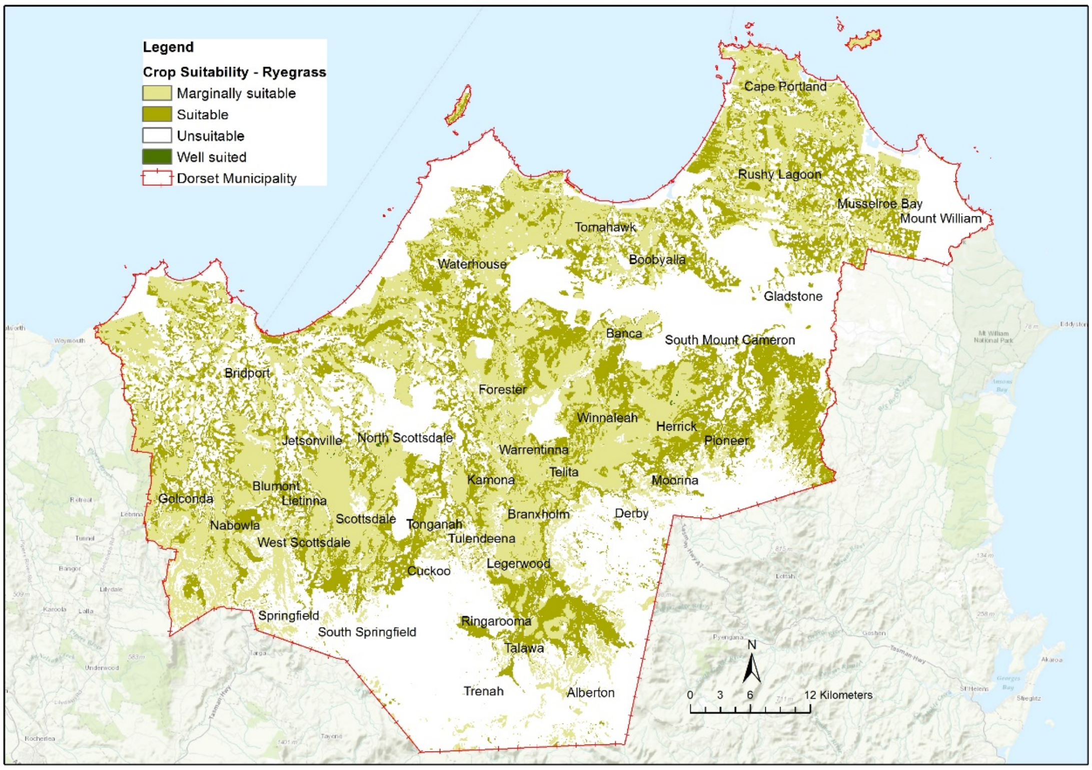


Figure 6-11 crop suitability for ryegrass

Based on the parameters initialised for Scenario 2, the number of farmers who adopted hemp decreased under the irrigation-expansion-scenario and the number of land parcels that produced ryegrass and poppy under the irrigation-expansion-scenario increased for the reasons outlined above. However, care does need to be taken in interpreting these results, since crop suitability is only one of the factors that influence decisions like that of the adoption of hemp under irrigation expansion, and the results might change under different parameters and assumptions. For example, other factors such as gross margin, the neighbours' proximity effect and crop rotation are also influential factors for farmers' production decisions under irrigation expansion. These examples of scenario simulations demonstrate their potential to provide data and spatial visualisations of different scenarios with differing parameters and assumptions. It is the capacity of the simulation to capture the different factors that influence farmers and better understand, not only the local land parcel effects but also the cumulative effects across the landscape. When used in this way scenarios can trigger thinking about consequences and impacts hitherto not considered – such as farmers not planting hemp, as might be assumed, but expanding areas under poppy and ryegrass. The important point to note is that the Crop GIS-ABM can capture these parameters and test assumptions.

6.2.3 Scenario 3 (S3)

The third scenario was a macro-scale scenario that focused on exploring the potential effects of farmers' decisions and behaviours on land use change in regards to agricultural commodity prices. In this macro-scale scenario, individual farmers cannot directly control the agricultural commodity price. Macroeconomic variables such as trade policy play a critical role in determining the price of agricultural products (Tomek & Kaiser 2014). For example, milk price is not governed by farmers; instead, macro-scale decision-makers (trading committees, policy makers, processing plants and retail companies) determine milk price based on market demands and agricultural policy.

Farmers’ expectations about the future price of agricultural commodities influence their decisions (Tomek & Kaiser 2014) and as the data discussed in Chapter Four showed, most of the participants in this study indicated that the market price plays an important role in their decisions on crops selected for production. In the first scenario, the adoption of hemp by farmers was explored, and in the second scenario, the effects of irrigation expansion on hemp adoption were examined. The third scenario explores how the market price of milk (because dairy on ryegrass pasture is an important enterprise) might influence farmers’ decisions on whether they might adopt hemp production. Crop GIS-ABM was used to simulate the farmers’ behaviour and interaction under different milk prices: specifically, the third scenario investigates whether, with an increase in the return price on milk products, the percentage of farmers who produced hemp decreased and the aggregate rate of hemp adoption declined in the Dorset region.

Initialisation

The market fluctuation for milk price influences dairy gross margin and shifts in the milk price change farmers’ expectations about the future prices of certain types of crops, which in turn affects farmers’ decisions on which crops they might produce. DPIPWE calculated that the gross margin for a dairy farm is around $3295/ha based on a price of $5.20/kg milk solids. If the milk price decreased to $4.68/kg milk solids, the gross margin dropped to $2768/ha, and conversely, if the milk price increased to $5.72/kg milk solids, the gross margin increased to about $3803/ha (Department of Primary Industries Parks Water and Environment Tasmania n.d.). This ±10% variation in gross margins was used to explore the sensitivity of milk price on spatial land-use outcomes.

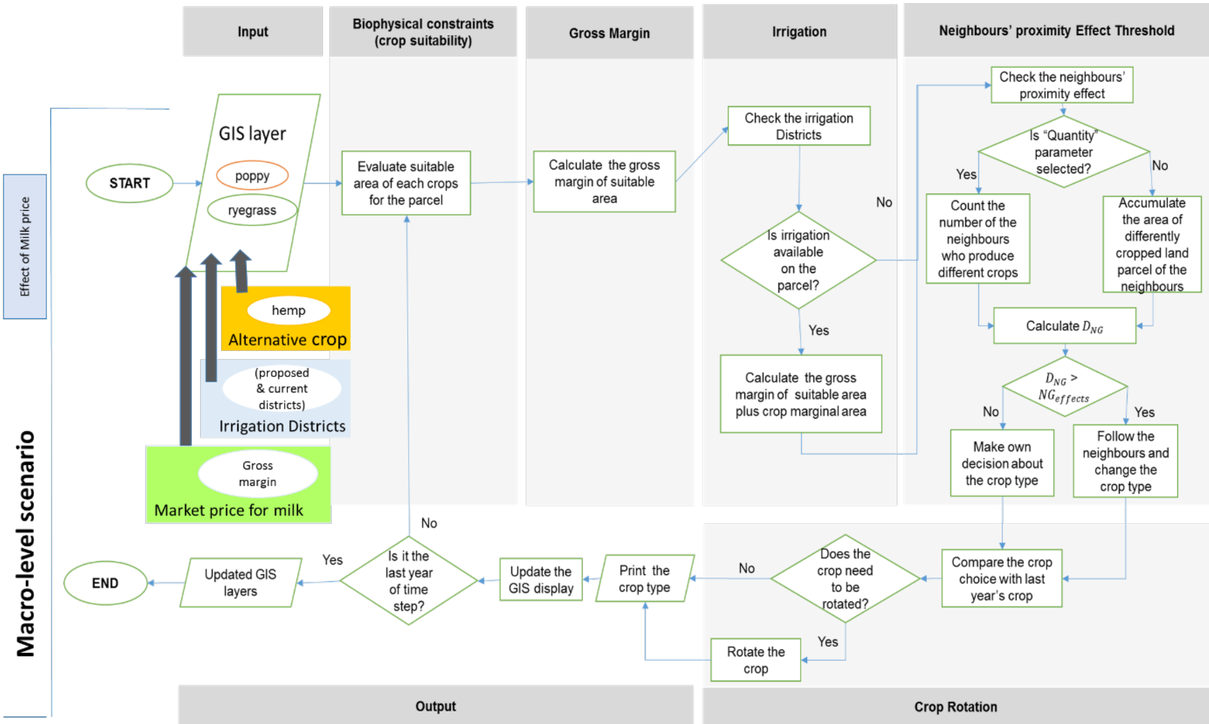
Ryegrass pastures are the mainstay of pasture-based dairy farming (Dairy Australia n.d.) and the interview data analysed in Chapter Four confirmed that ryegrass pasture for dairy farms and livestock is the most significant crop produced in the Dorset region. This being the case, the assumption for the third scenario proposed that if dairy farmers irrigate their land parcels, they could intensify ryegrass production and increase the dairy gross margin and productivity.

For the purposes of Scenario 3 the Crop GIS-ABM simulated the effects of the milk price on farmers' decisions under four experimental conditions and, as is outlined in Table 6-4, each experimental condition represents the milk price (high and low) with and without irrigation expansion.

Table 6-4 Experimental conditions (E) for the third scenario. MS = milk solids

Experimental conditions	**E1**	**E2**	**E3**	**E4**
Irrigation	No irrigation	No irrigation	Irrigation available	Irrigation available
Milk price ($ 5.2)	-10% $ 4.68	+10% $5.72	-10% $ 4.68	+10% $5.72

As with previous scenarios, the Crop ABM-GIS model was initialised with hemp, ryegrass and poppy randomly allocated to land parcels. Each Farmer agent decided which option was the best choice of crop for his/her land under the four experimental conditions summarised in Table 6-4. Figure 6-12 represents the flow chart of the decision process for the scenario: each farmer took into account crop suitability, calculated their gross farm margins for each particular crop per hectare and considered irrigation availability, the neighbours' proximity effect and crop rotation, and compared the enterprises.



(*) It is a parameter that give the model-user a choice between Quantity or Area rules (explained in section 5.3.1)
(**) It is an equation that calculates a ratio of the differently cropped neighbour parcels to the total neighbours (explained in section 5.3.1)
(***) It is Neighbours' proximity Effects Threshold (explained in section 5.3.1)

Figure 6-12 Flowchart for the effect of milk price on the decision-making process in the model

Input data for the Crop ABM-GIS model consists of the State irrigation company's (TI) map along with DPIPWE GIS layers and census data. The gross margins of the crops (hemp, ryegrass and poppy) were extracted from DPIPWE department documents (Macquarie Franklin 2012, 2018b, 2018a) and Table 6-5 lists the parameters used in the model for the third scenario.

Table 6-5 Parameter initialisation – Adoption of alternative crop under irrigation expansion

Parameter in Crop GIS-ABM	**Unit**	**Initialisation**	**Experimental conditions**	**Description**
InnovationAdoptersRatio	%	2.5	E1, E2, E3 E4	Adoption rate
PoppyGrossMargin	$	3030	E1, E2, E3 E4	Poppy gross margin
HempGrossMargin	$	1290	E1, E2, E3 E4	Hemp gross margin
RyegrassGrossMargin	$	2,786	E1	Ryegrass gross margin
	$	3,803	E2	
	$	2,786	E3	
	$	3,803	E4	
NeighboursEffectThreshold	[0-1]	0.3	E1, E2, E3 E4	The effect of neighbour's choice
MaxTimestep	Year	10	E1, E2, E3 E4	Maximum time step for simulation
Quantity	True/False	True	Crop dissimilarity within the neighbourhood	Quantity
Irrigation	True/False	True	The availability of the irrigation	Irrigation

The availability of irrigation expansion was based on the current and proposed irrigation districts as illustrated in Figure 6-4. In the first and second experiments (E1 and E2), the Crop GIS-ABM did not consider the irrigation expansion districts, but it did include input from the irrigation districts for simulations in the third and fourth experiments (E3 and E4). For each experiment, the simulation continued for ten years. The model stopped at the end of the time step, and the regional pattern of crops in the Dorset region under each experimental condition was visualised in the ArcGIS display.

<u>Scenario analysis (S3):</u>

The scenario of effects of milk price on the adoption of hemp was examined by asking: if the price of the milk increases, how many farmers might adopt a high-value new alternative crop, such as hemp, in comparison to producing ryegrass for dairy/livestock? In this scenario, the cumulative number of hemp adopters to total farmers can be used to demonstrate the tendency of farmers to adopt hemp under irrigation expansion, as well as the effect of the milk price on their decisions.

Two other points relevant to the simulation are noted. Farmer agents in the Crop GIS-ABM simulation select a crop type regardless of whether it is a traditional or new alternative crop – if the crop's gross margin covers the cost of irrigation investment for the farmers. If irrigation is available in the district, farmers calculated the crops' gross margins by securing water consumption, and on the basis of these data they then selected for production the crop type that was more profitable than other crops. Further, if irrigation is not available, the biophysical constraints of the farm land and crop rotation play a key role in farmers' decisions, and in these circumstances, they might be more sensitive to the market price of the crops. Table 6-6 illustrates the simulation results of hemp crop adoption under four experimental conditions in the Dorset region for ten years.

Table 6-6 Adoption of hemp under experimental conditions

Experimental condition	**E1**	**E2**	**E3**	**E4**
	No irrigation	No irrigation	Irrigation available	Irrigation available
	Low milk price	High milk Price	Low milk price	High milk Price
The accumulated number of Hemp adopters	310	212	291	166

In the first experiment (E1), it was assumed that irrigation was not available in the Dorset region and the price of the milk was relatively low during the ten years of simulation. The total number of farmers producing hemp was around 310. In the second experiment (E2), the assumption was that no irrigation was available, but the milk price was relatively high. The result of simulation under the second experimental conditions showed that around 212 farmers might choose to produce hemp over the ten years. The number of hemp adopters under the third experimental (E3) conditions (irrigation and low milk price) was around 291. In the fourth (E4) experimental conditions irrigation was available and the milk price was high, and around 166 farmers produced hemp. Looking across the results of the simulations for the experimental conditions, Table 6-6 clearly indicates (not surprisingly) that if irrigation is available and the milk price is high, more farmers will opt for dairy farming and fewer for a hemp crop.

The comparison of the simulation outcomes with and without irrigation expansion under different milk prices is also illustrated in Figure 6-13. As the graph shows, there is a nonlinear relationship between the market and the adoption of the new alternative crop with/without irrigation. Specifically, the simulation suggests that the farmers' decision is more sensitive to the milk price when they invest in an irrigation scheme, but only when the price of milk is low. This would suggest that when farmers invested in an irrigation scheme and the price of the milk has decreased, they were more likely to produce high-value alternative crops instead of ryegrass to cover the costs of irrigation. For example, the number of land parcels that produced ryegrass for dairy decreased by around 11% under irrigation expansion when the price of the milk declined from the default milk price of $5.20kg/MS.

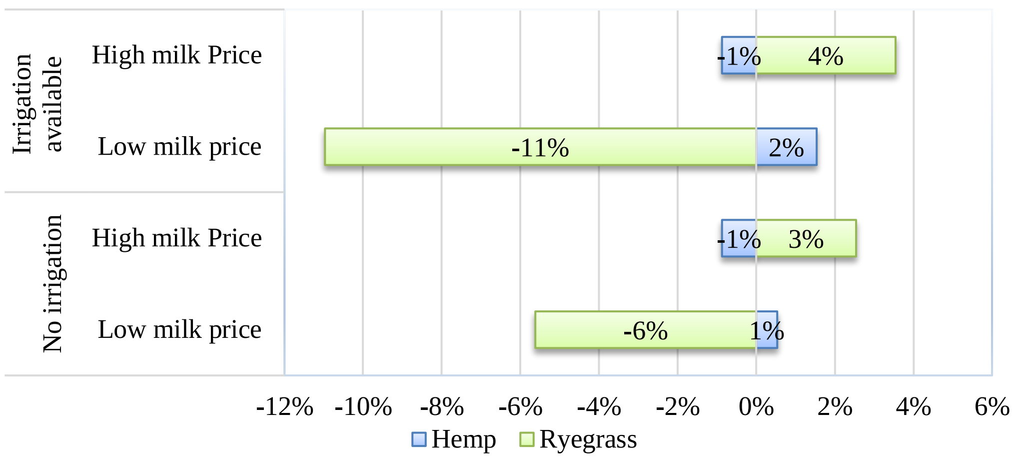


Figure 6-13 Comparison of hemp adoption under four experimental conditions

It can be concluded that farmers' crop decisions are based partly on the market price of milk, which is a common and well-established enterprise in the Dorset region, but alongside the milk market price the expected profitability of hemp will play a key role in the adoption decision. Again, the simulation data and comparison of the simulation results demonstrate that farmers' decisions about crop type are complex and nonlinear. The plausibility of the third scenario can be determined by comparing the results of the simulations (Figure 6-13). The simulation data affords an opportunity to consider several scenarios and impacts of different kinds of change such as fluctuations in commodity prices or changes in policy and the introduction of new crops (hemp and the changing legislation surrounding hemp is a good example). The simulation affords an opportunity to combine different factors and consider the consequences – such as the intensification of a traditional crop (as opposed to a new crop) like ryegrass cropping when the milk price is high, and the costs of irrigation are more than covered by the return on dairy investment and ryegrass.

Spatial analysis of scenario 3 (S3)

The spatial diffusion of hemp in the Dorset region under high/low milk price with/without irrigation expansion was analysed through the simulated maps. Figure 6-14 shows the spatial pattern of hemp adoption in the Dorset region under four experimental conditions. A summary of the spatial patterns shows:

- The land parcels that grew hemp under E1 (low milk price without irrigation) were clustered in three areas in the region during the ten years of simulation (North Scottsdale, Scottsdale, Bridport);
- The districts (e.g. North Scottsdale, Winnaleah, Derby & Rushy Lagoon) that grew the most hemp when milk prices were high but where there was no expansion of irrigation (E2);

- The hemp adopters under the third experimental condition (low milk price with irrigation) are concentrated mainly in three districts (Scottsdale, Winnaleah and Bridport) more than other areas; and
- The land parcels that grew hemp under E4 (high milk price with irrigation) decreased but the land parcels in three districts (North Scottsdale, Winnaleah, Rushy Lagoon) produced hemp more than other districts.

As Figure 6-14 shows, the pattern of hemp adoption changed in the Dorset region under different milk prices and the availability of irrigation. Although the land use patterns are dissimilar under different experimental conditions, the simulations show that some districts had more similarity than other districts. In the study region for example, West Scottsdale, Lietinna, South Spring and Golconda districts showed similar patterns regardless of different experimental conditions (milk prices and irrigation expansion).

The emerging crop patterns under four experimental conditions were compared to analyse the sensitivity of each pattern to milk prices and irrigation availability (Figure 6-15). Spatial analysis of the diffusion of hemp adoption under different experimental conditions indicates that some areas are more sensitive to milk prices and some areas are more sensitive to irrigation expansion. Comparing the emerged patterns under different experimental conditions showed that there are overlaps among the areas that are sensitive to milk price and irrigation availability, but there is an aggregation of areas sensitive to milk prices or irrigation.

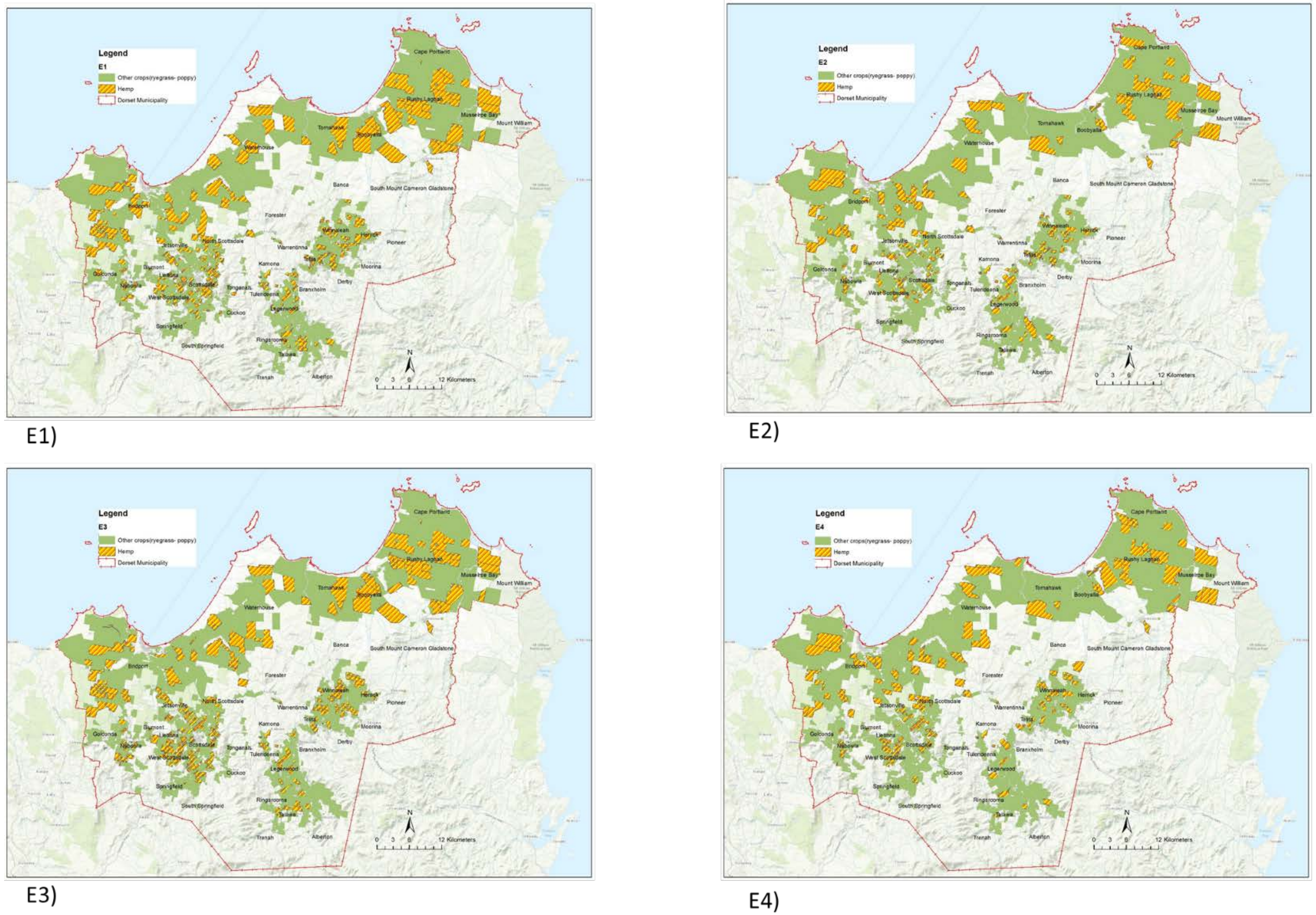


Figure 6-14 Spatial diffusions of hemp under four experimental conditions, E1) low milk price without irrigation, E2) high milk price without irrigation, E3) low milk price with irrigation, E4) high milk price with irrigation (Appendix 6 holds higher resolution maps)

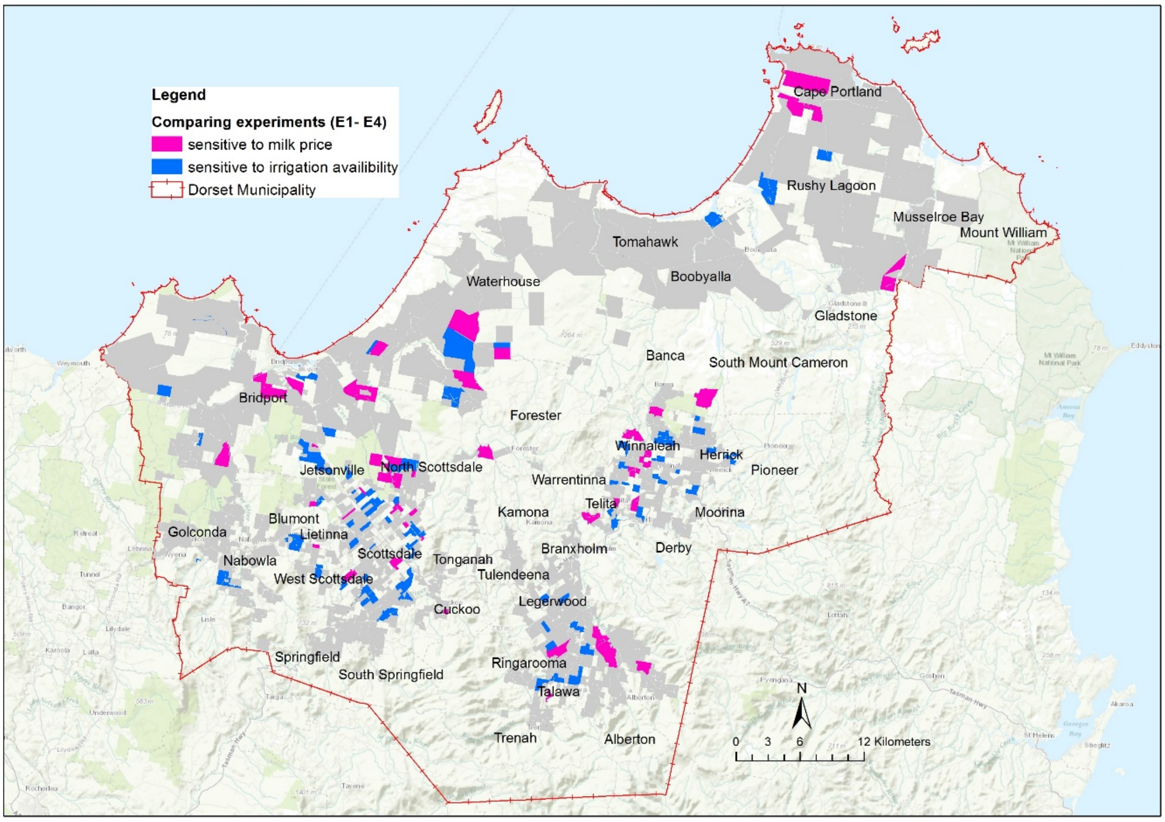


Figure 6-15 Spatial sensitivity of hemp adoption in four experimental conditions (E1-E4)

Figure 6-15 illustrates, for example, that there are spatial areas that are sensitive to milk price (i.e. North Scottsdale, Winnaleah, Waterhouse and Bridport). It means that the price of milk influences the farmers’ decisions in these areas more than the irrigation availability.

By contrast, other districts (Ringarooma, Scottsdale and West Scottsdale) are more sensitive to the availability of irrigation in comparison to the changes in the price of milk. The kinds of patterns exhibited by the simulations demonstrate that as input parameters are refined a more detailed understanding of land use decisions can improve planning and investment decisions both at the macro (regional stakeholders) and the local (individual stakeholders) scale.

6.3 Qualitative analysis of simulation outcomes

In Chapter Four, as part of a validity check for the study and assumptions underpinning the simulation model, the participants were asked to draw on a map of the Dorset region their perspectives on potential areas for alternative crops and irrigation expansion, based on their local knowledge and experience. In other words, a qualitative GIS technique is an analysis technique was used to collect the participants' spatial narratives around the adoption of the alternative crop.

The participants sketched the area where they felt farmers might be more interested in new farming systems such as irrigation or new crops/livestock. The sketched maps were used as a source of validation by comparing the simulation outcomes with the participants' mapped perceptions of the spatial changes that might happen in the future of the Dorset region.

Figure 6-16 illustrates the participants' sketched maps and shows which areas in their view might produce alternative crops. The sketched maps were scanned and transferred to GIS layers for analysis. The digitised sketch maps and the features were compared for common overlaps among polygons in ArcGIS software. Figure 6-17 shows the potential areas for alternative crops based on the participants' insights and the high overlap areas (more than 80% of participants) where farmers might tend to adopt new alternative crops. Most of the participants sketched the Waterhouse, Scottsdale, Ringarooma, Winnaleah and the North East districts of the Dorset region as potential areas for irrigation expansion and new alternative crop area.

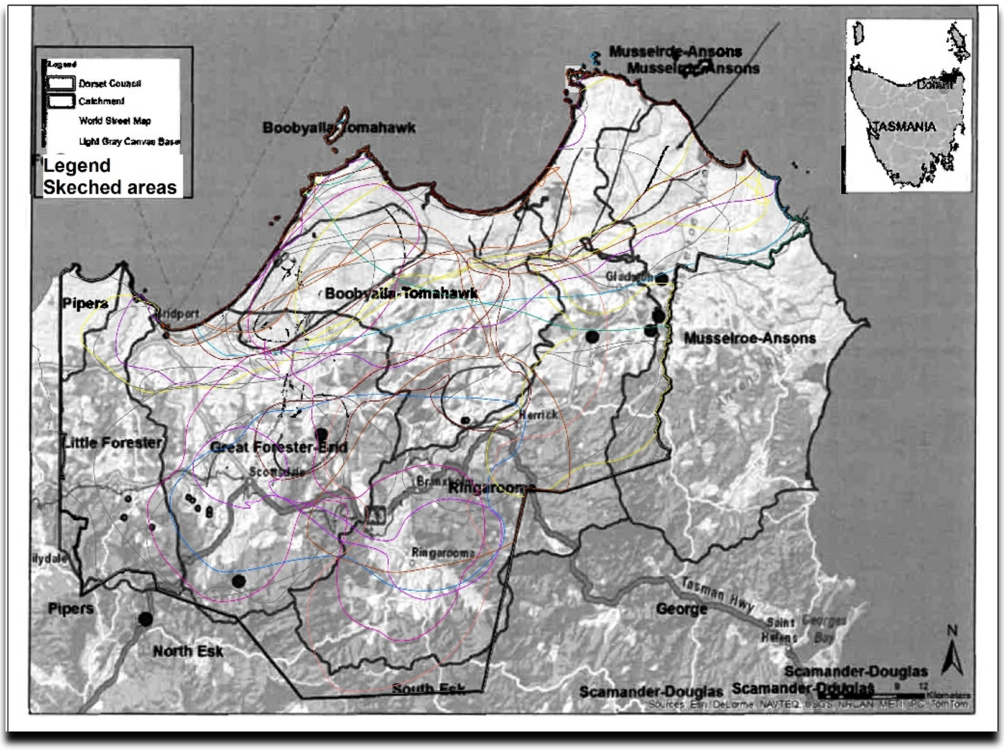


Figure 6-16 Digitised sketched maps by participants

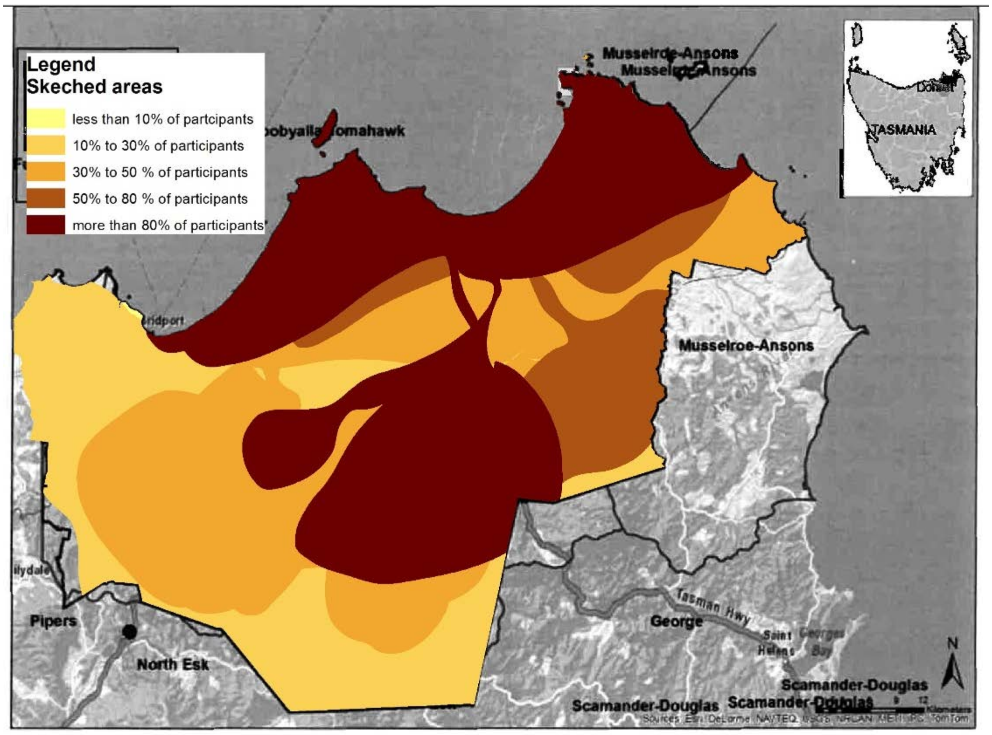


Figure 6-17 Overlaid areas for alternative crops and irrigation expansion by participants

The simulation outcome of hemp adoption produced by Crop CIS-AMB was compared with the digitised Participant Sketched maps to check the consistency and validity of the Crop GIS-ABM. The result of the hemp adoption simulation (Scenario 1 simulation) indicated that hemp might be produced mainly in Bridport, Ringarooma, Scottsdale, North Scottsdale and Ledgerwood after ten years. The comparison between the result of the Scenario 1 simulation (Figure 6-3) and the Participant Sketched map (Figure 6-16) shows that there is a similarity between the areas that participants sketched as having the potential for alternative crops, and the outcome of the Scenario 1 simulation. As the Crop GIS-ABM outcomes showed a good match with the participants' insights, it suggests that the model parameters reflect decision-making parameters expressed by participants quite well.

Comparing the results of the simulation with participants' sketched maps is not a rigorous criterion to validate the simulation model, but it improves the confidence level in using Crop GIS-ABM for testing the adoption scenarios. Moreover, using qualitative GIS techniques and the sketched maps supports the interpretation of emerging patterns in the simulations.

6.4 Summarising the third stage: the scenario analysis

This Chapter was designed to address the third research question (Q3) in this research by testing applications of Crop GIS-ABM to generate scenarios. Three scenarios were designed, developed and implemented. The initialisation of parameters for the specific scenario was described and the scenario findings and spatial patterns were then analysed.

The first scenario was designed to examine how farmers make decisions on the adoption of new alternative crops. The outcome of the simulation indicated the complexity of crop choice by farmers and the nonlinearity of farmers' decisions on crop types. It was shown, for example, that ryegrass pastures are popular among farmers and, that as a consequence, farmers might tend to intensify ryegrass for dairy/livestock or poppy instead of producing a new alternative crop. Spatial analysis of the first scenario revealed that the size of the farm is not the significant factor for decision-making about alternative crops so long as the overall profit in the adoption of hemp can be achieved, and the participants' insights support the spatial findings on the size of the farm.

The second scenario investigated how irrigation expansion promotes the diffusion of alternative crops in the region. The outcome of the simulation indicated that different factors such as the popularity of the ryegrass and poppy and the biophysical conditions especially the area of marginal land per land parcel play an important role in crop selection. For example, the number of farmers who adopted hemp decreased under an irrigation expansion scenario, and the number of land parcels under irrigation expansion that produced ryegrass and poppy increased.

The third scenario was designed to probe the complexity of decision-making further by focussing on the effect of commodity prices on farmers' decisions and how farmers' crop choices altered the land use and crop patterns. Because of the strong relationship between milk price and ryegrass pasture for dairy cattle, milk price fluctuations were utilised as a key driver for the Scenario 3 simulation. The simulation revealed that when farmers invested in irrigation and the price of milk decreased, they were more likely to produce high-value alternative crops instead of ryegrass as a strategy to cover the costs of irrigation. The spatial analysis of the diffusion of hemp adoption under different experimental conditions indicated that some areas are more sensitive to milk prices and some areas are more sensitive to irrigation expansion based on the biophysical condition, especially marginal land as well as irrigation availability.

To sum up, the Crop GIS-ABM was tested by developing scenarios based on farmers' crop choices under different agricultural scenarios. Beyond the specifics of crop types that farmers choose, the purpose of scenario analysis is less about an emerged pattern itself, but more about answering questions raised by the scenario. As Steinitz (2012) advocates, this is a highly effective means to test a range of possibilities, including questions such as why the pattern occurred, how Crop GIS-ABM performed and what new information was presented for interpretation.

The simulation model shows the capability of Crop GIS-ABM to be used as a tool for exploring the possible impacts of agricultural policy by considering the farmers' behaviours and interactions in the long term. Spatial visualisation of the emerged patterns of crops under each scenario provides insights into the complex relationship between farmers' behaviours, agricultural land use and adoption of agricultural innovation.

Notwithstanding the limitations of Crop GIS-ABM, it can assist decision-makers to better understand the possible patterns of crops and agricultural land use changes that might emerge in the future because of their decisions.

6.5 Crop GIS-ABM: strengths and weaknesses

The Crop ABM-GIS was used to simulate the complexity of the decision-making process by Farmer agents under different agricultural scenarios. The Crop GIS-ABM helps to explore questions such as why, how, when, where and what might happen in the future, if important decisions, strategies or policies were implemented today. It is important to recognise that as with any model there are both strengths and weaknesses in the model development and implementation.

Crop GIS-ABM was build based on a bottom-up approach to facilitate understanding of how cumulative decisions by farmers may affect the agricultural landscape in a region. The model can simulate patterns of land use change that are generated from farmers' behaviours and interactions. That said, Crop GIS-ABM was designed based on qualitative data and informed by interviewing different stakeholders. While analysis of these insights has been rigorous and would seem to identify key or influential factors that inform the model rules and assumptions, it is important to note these insights offer a valid starting point for a conceptual model of farmers' decision behaviours, which further research may enhance. However, the scenarios implemented in Crop GIS-ABM were based on assumptions that the agent's behaviour was fully informed and rational and was the optimal decision on crop type.

The Crop GIS-ABM algorithms were designed based on stakeholders' insights about how farmers make decisions on adoption of new crops or technologies. In Crop GIS-ABM, the agent's behavioural rules and model parameters and assumptions were not operationalised based on theory. The merged interpretation of interview and survey questionnaire findings was the basis for conceptualising farmers' decision-making. The model was informed by stakeholders' insights rather than a specific theory. Crop GIS-ABM was built based on a mixed method design approach that facilitates the integration of qualitative and quantitative data. This model has a better reflection of farmers' decision processes who live in the region as the parameters and rules were designed based on their insights.

Indeed, the Crop GIS-ABM is constrained by its stakeholder-based assumptions and parameters. Different stakeholders were interviewed to gain a better understanding and simplify the complexity of decision-making on agricultural land use. Interview data provides insights on the influential factors, but there might be other factors not mentioned by interviewees.

The conceptual model was necessarily simplified, and the Crop GIS-ABM was designed based on the simplified conceptual model of the decisions of farmers who live in the Dorset region. However, the scenarios implemented in Crop GIS-ABM were based on assumptions that the agent's behaviour was fully informed, rational and was the optimal decision on crop type. There were also some limitations and constraints for converting different types of GIS data. Converting raster pixel data to coordinate vector data created changes in the scale and size of the input data.

One of the advantages of using Crop GIS-ABM is its flexibility. The Crop GIS-ABM algorithms were built using Not Quite Python programming language. The Crop GIS-ABM was designed based on middleware approaches that include both ABM and GIS features. A strength of the Crop GIS-ABM is the way in which it affords an opportunity to test different scenarios to simulate cumulated impacts of farmers' (micro-scale) decision under different parameters and visualise the impacts of the assumptions and scenarios in ArcGIS. The model-user can change the parameters and run the model under different assumptions (e.g. gross margin) and explore the consequences of parameter changes (e.g. different gross margins). This model has the flexibility to import from different GIS layers and display the outcomes of simulation as maps, where a similar real-world experiment would be time-consuming, expensive and entirely impractical.

The robustness of Crop GIS-ABM was tested by employing a sensitivity analysis method. However, the Crop GIS-ABM has some intrinsic limitations, for example model calibration and validation, that are common to all spatial ABMs.

Chapter 7: Discussion

7.1 Introduction

The thesis began by proposing that land use planning in Australia is very oriented towards urban planning. This is for good reason, given the density of Australians living in cities along a relatively narrow coastal band. However, this band also contains some of the most arable land, well suited to agriculture. Thus, for this reason alone, it could be argued there is a need for land use planning to have a greater focus on agriculture. That it is needed is seen in land use conflicts surrounding the rural-urban interface (Schirmer 2018). Urban encroachment into agricultural land, climate change and water security are complex issues that threaten the agricultural landscapes.

Countries such as the United Kingdom and some in Europe have a strong focus on the preservation or protection of their agricultural landscapes because of these concerns. For example, preserving and managing rural and agricultural land use is a part of a broader EU investment strategy for responding to the various economic, environmental and social challenges of the twenty-first century (European Commission n.d.). Similarly, in the UK, the Countryside Commission aims to conserve and enhance England's countryside (Natural England 2007), and developed methods to assess differences in the natural and cultural dimensions of agricultural landscapes (Warnock & Griffiths 2015).

As a starting point, this study argues that agricultural land use planning in Australia requires a new innovative planning approach to balance the sustainability of agricultural production with conservation of natural resources. This complex planning process requires new and appropriate land use planning tools, and in this study, it is argued that a critical approach is one that provides support to increase decision-making efficacy and land use planning efficacy toward the best possible future for agricultural regions. Recognising this, Thackway (2018) notes the importance of using the latest scientific modelling tools for land use planning and natural resource management.

In particular, the study argues the need for a modelling and simulation tool that captures the voice of key stakeholders responsible for day to day operational land use decisions related explicitly to agriculture. Stakeholders, in this study, are most often the farmers but also are key policymakers and government agencies and businesses who may be responsible for macro-scale decisions about agriculture (recognising that more often than not the implementation decision or response rests with farmers).

Thus, the focus of the thesis was to develop a decision support simulation tool that is suitable for agricultural land use planning by incorporating the factors that influence farmers' decision making. While agricultural land use planning *per se* has been neglected (as noted in Chapter Two), for some time a significant body of work utilising geographic information systems (GIS) has informed landscape planning and a broader scope of environmental planning. Thus, GIS has been a critical building block in this study in the development of a practical decision support tool. So too was agent-based modelling (ABM), mainly involving integration of ABM with social factors. While not focused on agriculture, Gilbert's ground breaking work on simulation for social phenomena (Gilbert & Troitzsch 2005), and public policy (Gilbert et al. 2018) has demonstrated an opportunity for this study to include social factors and the use of ABM systems to develop simulation tools that generate scenarios in agriculture.

The body of the study, therefore, is about the construction by the author of a simulation model or decision support system – Crop GIS-ABM. The development process was a multistage three-step process, and was very much informed by the geodesign methodology developed by Steinitz (2012) as a landscape planning and design strategy. The application of the three-stage process (which commences with qualitative research into farmers' decision making) and the development, from the bottom-up, of the Crop GIS-ABM by the researcher, is a core focus of this research. Chapters Four, Five and Six describe how this was done. In this Chapter, several key themes that emerged through the process of building an agricultural land use planning simulation model (Crop GIS-ABM) are discussed.

7.2 A role for and the importance of agricultural land use planning

The underlying premise for this study was the need for an approach to land use planning that accounted for the impact of farmer decision making – the argument being that the cumulative impact of these decisions is significant for land and water resources in Australia. Tasmania was selected as a case study, for largely pragmatic reasons of proximity, local relevance and available GIS data. That said, the reliance of the State's economy on agriculture and its role into the future for Tasmania along with significant investment in irrigation as a strategy to support agriculture all reinforce the need for more informed decision-making around agriculture. As Hicks (2018) has stated, planning for agricultural land use is challenging especially when considering a significant change to the landscape like irrigation expansion that has widespread effects on farming practices. Agricultural land use change is not purely the result of biophysical conditions. The agricultural landscape in

Australia is also experiencing considerable pressure from both development and conservation lobbies as well as facing challenges such as climate change. It is also a result of complex interaction between (1) human behaviour and decisions and (2) natural resource and spatial conditions.

This study pays attention to the importance of the interaction between policy and farmers' decisions about their land or the land they farm. This study highlights that: (1) there are direct and indirect interactions between policies and farmers' decisions, (2) agricultural land use is dynamic and changes over time, and (3) the effects of a farmer's decision on agricultural enterprises extends beyond his/her agricultural land.

7.2.1 Planning to understand agriculture in the 'bigger land use picture'

In Chapter 6 (scenario analysis), farmers' decisions on the adoption of new alternative crops/livestock were simulated over time to explore how micro-scale farmers' decisions change macro-scale agricultural crop patterns in regions. Comparing the emerged patterns under different experimental conditions highlighted the range of scenarios characteristic of farmers exercising land use options. The scenarios showed that the size of the farm may not be a significant factor for decision-making on alternative crops as long as the overall profit of adoption of the new alternative crop (e.g. hemp) can be achieved. By simulating irrigation expansion, it was possible to understand that Farmer agents can potentially choose to access and adopt irrigation to intensify ryegrass and poppy production in their land parcels rather than choosing to grow a new alternative crop. Scenarios also afforded the opportunity to see what unfolded when there was a change in a key/core commodity price. The benefits of simulating a range of scenarios are that several possible changes in agricultural land use can be considered, which provides an opportunity to consider not only possible impacts but policy agendas.

7.2.2 Planning to 'hear the farmer's voice'

This study has illustrated the interaction among farmers who live in a region and demonstrates how the accumulated effects of their interactive decisions changes agricultural land use patterns. For example, the spatial diffusion of hemp in the Dorset region under irrigation expansion highlighted that the number of land parcels that grew hemp was clustered in some areas. A farmer's decision on adoption of irrigation to improve the biophysical condition of their farm by transferring marginally suitable areas for crop production to suitable land not only changes his/her farm enterprise but also the cumulative effect of farmers' decisions changes the agricultural landscape over time. These examples of scenario simulations demonstrate the capacity of the Crop GIS-ABM to capture the different factors that influence farmers and their decision-making. This approach offers an innovative method to incorporate stakeholder decisions and choices not easily achieved in traditional land use planning approaches and systems.

7.2.3 Decisions about agriculture on land parcels and the cumulative impacts

The study shows how the land parcel, as a fundamental building block in GIS, is an important organising framework for agricultural land use planning using a simulation tool. Decisions about types of agriculture on land parcels is a fundamental part of farming operations. This research demonstrated that a spatial ABM is a useful tool for agricultural land use planning because its structure allows for simulating the interaction between policies and individual farmers' decisions where the agent (Farmer) can be linked to GIS land parcels. It enables exploration of the complex effects of agricultural policy and planning on land use change. For example, the spatial ABM (Crop GIS-ABM) that was developed in this research allows not only for tracking the behaviour of individual farmers over time but also for simulating agricultural land use patterns that might emerge under different agricultural policy scenarios (e.g. irrigation expansion).

7.3 Integration of ABM and GIS in Crop GIS-ABM: connecting the human-nature interface

This study was timely in the field of agricultural land use planning because, although ABM and GIS approaches have been around for a few years in this space, they have rarely been linked with stakeholders' insights. The value of ABM lies in its capacity to account for socio-economic factors and conversion of these factors through algorithms to represent characteristics of human decision, behaviours and interactions. Spatial ABM was shown in this study to be a practical and flexible simulation tool that could be useful for agricultural land use planning and scenario testing. This is because of the ability of spatial ABM to explore the complexity of farmer-agricultural land system interaction by considering a farmers' decision model. As Matthews et al. (2007) have highlighted, the advantages of the ABM approach in land use studies lies in its ability to dynamically link social (human) and natural system (land) processes. The ABM approach in this study affords the opportunity to (1) model the individual farmer's decision-making process, (2) simulate their interactions with each other and their land, and (3) capture the economic, social and environmental heterogeneity among farmers (agents).

Similarly, as discussed in Chapter Two, there has been a considerable body of work done on GIS and its application to spatial planning during the last thirty years. The body of work affirms the importance of spatial data and land and water resource information to land use planning (Parker, DC et al. 2002; O'Sullivan & Perry 2013; Thackway 2018). This study drew on this body of work in GIS as a fundamental spatial platform for this research. It is the integration of ABM and GIS that has enabled the researcher to pull the qualitative and quantitative data together and combine socio-economic factors with the spatial data.

In this research, the conceptual basis of Crop GIS-ABM is the farmers' decision model. The conceptual model of farmers' decisions was designed by capturing various stakeholders' insights, and the algorithmic basis of Crop GIS-ABM was structured in a way to reflect the conceptual model of farmers' decisions. These algorithms are unique in not only capturing stakeholders' insights on how farmers make decisions but also in capturing the heterogeneity among farmers' decisions and their interaction with their lands. As has been established it is this kind of data that is intrinsic to effective agricultural land use planning and a fundamental contribution by this study to extending the capacity of ABM-GIS. The research demonstrates how parameters such as social, environmental and economic factors can be synthesised in Crop GIS-ABM, bringing spatial and ABM data together.

7.3.1 From the bottom-up

As has been identified in previous sections, this study utilised software and GIS as the tools to integrate human and natural biophysical characteristics. Previous studies (Lesslie & Mewett 2013; Hicks, W, Viscarra Rossel & Tuomi 2015; Lawrence et al. 2018) demonstrate that the advances in spatial technology and scientific modelling approaches have improved monitoring and reporting of land use change. That said, current biophysical models of land use, e.g. Multi-Criteria Shell for Spatial Decision Support (Hill et al. 2005; Lesslie & Mewett 2013) are generally top-down in their approach and do not link micro-scale human data to the biophysical and land use data in GIS.

In this study, rather than a top-down approach, the Crop GIS-ABM model was built from the bottom-up. This study began with stakeholders who live, experience and make decisions about farming that trigger agricultural change. This points to the need for an approach that captures this kind of decision making. A bottom-up simulation model was developed because the research problem identified that it is the farmer-level decisions (which cumulatively have a significant impact on land use and landscapes) that are either not included or considered too difficult to obtain to include.

The top-down perspective on land use planning, despite some weaknesses, has shaped planning practice (Murray, M et al. 2009) and it is an appropriate mechanism for setting an over-all vision and policies for land use (Pissourios 2014). However, using a bottom-up simulation model alongside top-down land use planning can facilitate a better informed policy formulation process by simulating the possible impacts of the policy in the future.

While a bottom-up approach such as ABM (and by implication the Crop GIS-ABM) does not provide all the information for agricultural land use planning, it does tackle the complexity of the decision-making process from a different angle (discrete choices by farmers). Furthermore, considering the insights of stakeholders who are experiencing the change, it also facilitates an opportunity to build and represent a shared understanding of the decision-making process on change, for example the effects of irrigation expansion as examined in this study.

The approach adopted in this study introduces a way of strengthening the simulation outcomes through integration of stakeholders' insights and considerations into the algorithms and parameters. This study points to the importance of the integration of theoretical knowledge and stakeholders' knowledge through a set of computer-based techniques and rules to help more informed scenario testing. This research illustrates how the integration of stakeholders' insights and knowledge within a spatial ABM provides a better understanding of the influence of dynamic human behaviours on the emergence of regional land use patterns.

7.4 Merged interpretations

Given the important role of farmer insights in underpinning a conceptual decision model for this study, an important contribution was the way in which this data could be meaningfully interpreted and integrated into the modelling. The process by which this was achieved in this study was through ‘merged interpretation’.

The pragmatic approach adopted in this study allowed for multistage mixed method design to collect and analyse qualitative and quantitative data. Merged interpretation is drawn from the intersection of qualitative and quantitative datasets comprising interview and survey questionnaire findings. From these findings, which yielded an in-depth understanding of the participants’ insights, it was possible by a process of merging (outlined in Chapter Four) to extract the most influential decision factors that affect farmers’ choices, despite the small number of participants. Merged interpretation offered a rigorous approach to conceptualise a farmers’ decision model and its subsequent integration into a spatial ABM.

Finally, the simultaneous display and comparison of participants’ sketched maps with simulated maps also provided an example of how qualitative data might be intersected with spatial maps, providing a useful check to assess to what extent the simulated outcomes were aligned with participants’ insights. This study demonstrated that the merged interpretation of qualitative and quantitative data can assist in looking at agricultural land use from different perspectives. Merged interpretation of both data provides an in-depth understanding of the factors that influence farmers’ decisions as well as some aspects of relationship and connectedness among the factors.

7.5 Simulation & scenarios

This research argues that it is important for agricultural land use planning to gain insights into land and water resource options before implementation of agricultural policy and development of land use options in a region. One approach developed in this study was to simulate agricultural scenarios to consider a set of alternatives and possibilities that might emerge in the region by exploring the human-environment interactions under different agricultural policy and land use decisions. In this study, Crop GIS-ABM afforded opportunities to simulate agricultural scenarios to explore the possible impacts of agricultural policy on land use (e.g. irrigation expansion).

This research, however, did not focus specifically on the outcomes of scenarios *per se* as there are many possible scenarios that could have been analysed. The model did not have an exhaustive number of explanatory variables as it was premised based on interview and survey questionnaire results from participants in the Dorset region. Instead, the central aim of the study was to explore the potential for simulation for agricultural land use planning. This involved three critical research steps. First, to identify the possibility of constructing a spatial agent-based simulation model in a computational setting. Second, and more particularly, to develop a simulation model that could capture the kinds of ‘local’ decision factors that are intrinsic to agricultural production, farming systems and associated land use activity. And third, in that context, to show that it is possible to develop a spatial ABM that embeds stakeholders’ insights and integrate ABM data with spatial data, and from that model run a range of scenarios to look at possibilities and potential land use impacts. Of course, not all stakeholders’ insights have been captured and not all the potentially available qualitative data and quantitative data have been integrated into the simulation model.

There is a place for a simulation model and scenario generation in land use planning. The study has shown the importance of designing a decision support simulation tool that reflects how farmers make decisions under changing conditions such as introducing a new irrigation scheme or new alternative crops. A simulation model that reflects stakeholders' insights brings both scientists and non-scientists stakeholders' insights and values together to tackle the social complexity of decision-making processes.

7.5.1 Adopting a multi-stage research design approach

The multistage research design of this study was adapted from the geodesign methodology, especially agent-based design as articulated by Steinitz (2012). The multistage research design enabled an iterative approach to be applied to the development of the Crop ABM-GIS model. Steinitz (2012) notes that effective design thinking happens through a series of iterative stages, and stages are proposed relating to 'why' questions (first iteration), 'how' questions (second iteration), and 'where, when and what' questions (third iteration).

In this study, the first iteration focuses on understanding the geographic study area (i.e. the 'why' questions), the purpose of the second iteration is to develop a methodology based on stakeholders' decision criteria (i.e. the 'how' questions) and the third iteration is to simulate different scenarios and the alternative futures (i.e. the 'where, when and what' questions) (Steinitz 2012). Further, in the geodesign three-iteration framework, six questions are asked (explicitly or implicitly) over at least three iterations and answered by six models. The questions are: how should the study area be described?; how does the study area operate?; is the current study area working well?; how might the study area be altered?; what differences might be the changes cause?; and how should the study area be changed? (Steinitz, 2012).

This iterative design process developed by Steinitz (2012) provides a relevant and purposeful framework for this study. While this study was informed by a geodesign framework and the six main questions, the multistage design was developed by the researcher. Figure 7-1 demonstrates how the multistage design of this study was informed by the geodesign framework and attributed to the different stages. The answer to the first question abstracts the information required for building a Crop GIS-ABM (Steinitz (2012) refers to this as Representation Model) and determines the scope of this study. The second question explains the functionality and relationship among farmers’ decisions and agricultural land and provides information for analysis assessment of most influential decisions’ factors (Steinitz (2012) referred to this as the Process Model). The third question is answered based on the value and insights of stakeholders and decision-makers and explains the conceptual model of farmers’ decisions (Steinitz (2012) refers to this as the Evaluation Model). In this study, these three models referred mainly to the past and the existing conditions of the agricultural land in the context of the study’s particular geographic context.

The fourth answer helps form the future conditions (the Change Model) by designing the algorithms and building the ‘change simulation’ (Crop GIS-ABM). The fifth answer is based on the process model under changed conditions (Steinitz (2012) refers to this as the Impact Model), and analyses the agricultural Scenarios. The answer to the sixth question depends on the evaluation of alternatives based on stakeholders’ preferences (Steinitz (2012) refers to this as the Decision Model). It should be noted that participants’ sketched maps were used for assessing the simulation results rather than the real local public stakeholders to overcome the challenge of insufficient time and other resources in this study. The Change Model, Impact Model and Decision Model (fourth, fifth and sixth in the iterative sequence) concern the future more than the past and present.

This study has therefore demonstrated the usefulness of iterative design thinking and the geodesign process as a frame within which to consider land use planning. Figure 7-1 maps the multistage design process for this study against the Steinitz framework, illustrating the value and application of iterative design thinking for complex planning such as that required for agriculture. This study has also showed that, despite some limitations of Crop GIS-ABM, it can assist decision-makers to better understand the possible patterns of crops and explore agricultural land use changes that might emerge in the future because of farmer-based decisions.

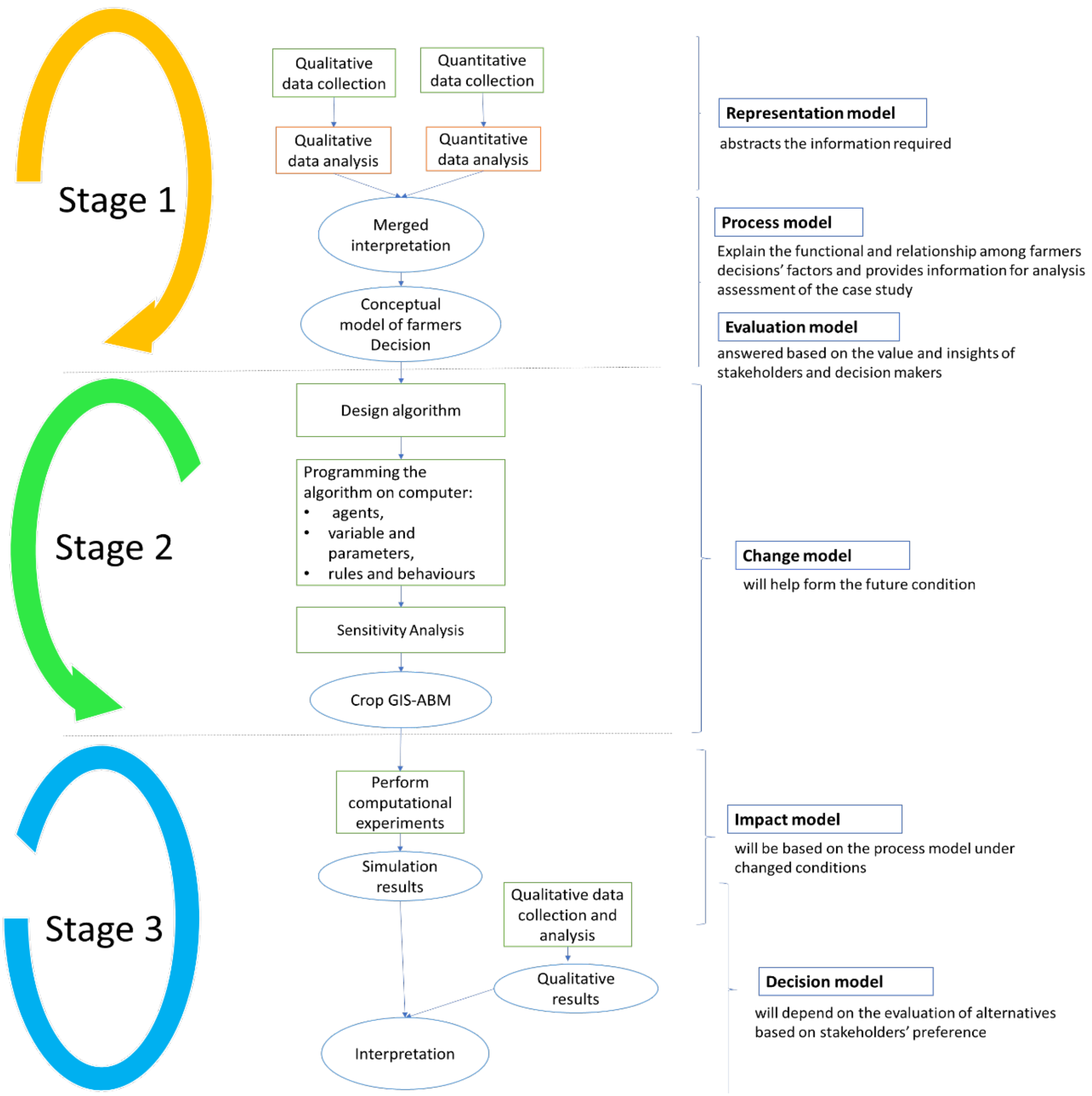


Figure 7-1 Relationship between multistage design of this study and geodesign framework

Conclusion

This thesis addressed some key gaps in agricultural land use planning, such as the failure of many approaches to land use planning to consider stakeholders' (farmers') decision model and human-land use interaction or the spatial effects of the adoption of agricultural innovation. In that context, the overarching theme and the primary question of this research was whether agricultural land use planning in Australia needs a decision support simulation tool, and if so, what type of simulation tool might be useful and how might it be developed.

This study highlights that: (1) there are direct and indirect interactions between agricultural policies and farmers' decisions, (2) agricultural land use is dynamic and changes over time, and (3) the effects of a farmer's decision on agricultural enterprises extend beyond his/her agricultural land (4) agricultural land use is influenced by not only multiple aspects of biophysical and socio-economic processes but also the accumulated effects of farmers' interactive decisions (5) spatial ABM can facilitate a better-informed agricultural land use planning by simulating the possible cumulative impacts of individual farmer decisions and interactions where the agent (Farmer) can be linked to GIS land parcels (6) the multistage research design enabled an iterative approach to be applied to the development of the spatial ABM.

The Crop GIS-ABM makes an important contribution to the literature on spatial ABM simulation because it includes stakeholders' insights and integrates both qualitative and quantitative data into spatial ABM. The algorithms are unique in not only capturing stakeholders' insights on how farmers make decisions but also synthesising different influential factors in Crop GIS-ABM. These factors are the biophysical characteristics of the farmers' land parcel (adopted from Crop Suitability Map developed by DPIPWE), economic factors (adopted from crop gross margins developed by DPIPWE), irrigation availability (adopted from irrigation districts developed by TI), Neighbours proximity effects and considering the crop rotation factors into Crop GIS-ABM. This study contributed to the body of knowledge by demonstrating that (1) agricultural land use planning in Australia can benefit from using a decision support simulation model, (2) spatial ABM is a useful model for land use planning and (3) the multistage research design of this study facilitates the process of developing the simulation model and answering the research questions. Further, a series of sub-questions were asked to facilitate the research design, data collection, scenario testing and exploration of a spectrum of possibilities. The first of these sub-questions investigated economic, social and environmental factors that might influence farmers' decisions on crops/livestock choice. The second question examined the integration of qualitative and quantitative data with an ABM in a GIS-based 'virtual laboratory'. The third question explored the Crop GIS-ABM's potential for simulating different agricultural scenarios and spatial visualisation of the possible impacts of farmers' crop choices on agricultural land use patterns.

Answering these questions required the incorporation of some attributes from both qualitative and quantitative data. Thus, the overall approach of this research was pragmatic, using mixed method research for data collection and analysis, for example, to study how farmers' decisions change the patterns of agricultural land use. The study adopted a multistage research design which provided a structured process to integrate the methods and techniques needed to address the research questions and build a simulation model.

The first stage addressed the question of the integration of accurate and useful data to scope the important influential factors that affect farmers' choices. Qualitative data through semi-structured interviews and quantitative data via a questionnaire were collected and analysed to pull themes together. The merged interpretation of both data provided insights and a better understanding of the key factors that affect farmers' decisions. Two scales of decision making (macro-scale and micro-scale) and their interaction were considered. A conceptual model of farmers' decisions was designed based on key factors, allowing the model to accommodate the interrelationship of the micro-scale and macro-scale decision process.

The second stage focused on how to design and integrate the conceptual model of farmers' decisions into a simulation model. The conceptual model was transferred to algorithms, and the ABM data and spatial data were linked. The simulation model was developed by combining socio-economic data with spatial data in Agent Analyst software and called Crop GIS-ABM. The result was in effect a 'virtual laboratory' for conducting simulated agricultural experiments.

The third stage focused on 'testing' the ability of the Crop GIS-ABM to simulate the effects of 'change' scenarios on agricultural land use change. Different agricultural scenarios were simulated to investigate the possible impacts of farmers' crop choices on agricultural land use patterns. The simulation experiments were conducted by changing the parameters and input data to explore the possible effects of introducing new alternative crops and irrigation expansion. The outcomes of simulations were then analysed to investigate how farmers made decisions on adoption of new alternative crops/livestock and irrigation expansion, visualised in maps that were then compared with participants' sketched maps (qualitative data). Although comparing the simulated maps with participants' sketched maps is not a rigorous criterion to validate the simulation model, it helped to check the reliability and increase the confidence level in using Crop GIS-ABM.

Beyond the specifics of crop types that farmers chose, the Crop GIS-ABM was able to accommodate the complex interrelationship between farmers' behaviour, agricultural land use and adoption of agricultural innovation. Crop GIS-ABM demonstrated its capability to be used as an object-oriented spatial tool for exploring the possible impacts of agricultural policy and scenarios. It has shown the potential to be a valuable decision support tool in agricultural land use planning.

Recommendations for future research

This research recommends some possible areas for further investigation not only in agricultural land use planning but also in areas that explore changes that happen over time because of human-natural system interaction. Some key areas for future research have been identified as follows:

- The application of Crop GIS-ABM (with appropriate modifications) in other regions to test other public policy, scenarios, change and innovation;
- Application at different scales and instead of a region, consider a cluster of regions;
- Further refinement to link different crops suitability layers to the Crop GIS-ABM to simulate more complex problems.
- Further research to explore how much simulation results reflect the real world.
- The Crop GIS-ABM is constrained by its stakeholder-based assumptions and parameters in the Dorset region collected through interviews and survey;

further research could be done to explore how farmers in other parts of Australia and the world make decisions and what factors drive their decisions.

- Crop GIS-ABM is a tool that has the potential to be developed as a smart mobile application for helping farmers and other stakeholders to make more informed agricultural decisions.
- Further research could be done to explore how different types of farmers (e.g. the scientific vs traditional farmers or dry land farmer and red land farmer) decide on what crops to grow, how the nature of ownership influences their decisions and what the cumulative impacts of their decisions might be on land use change.
- Further research could be done to investigate the direct and indirect impacts of climate change, natural hazards and crop disease on farmers' behaviour and crop choices.
- Further research could be done to explore the validity of Crop GIS-ABM by through triangulation of the result of the models with a modified Delphi or stakeholder expert group feedback on assumptions and key findings.

Practical application

The methods and techniques along with the Crop GIS-ABM model itself have a number of practical applications. These potential applications are summarised as follows:

- The workflow of developing a spatial ABM and the Crop GIS-ABM that was developed in this study affords opportunities for local applications. Tasmanian Irrigation, for example, could use the Crop GIS-ABM for scenario analysis in irrigation expansion regions to explore the possible impacts of implementation decisions on land use changes. Others, such as farmers, land use planners and policymakers (e.g. local government) can use Crop GIS-ABM as a tool to gain insights into agricultural land use change and irrigated land options.

- The flowchart and algorithms of Crop GIS-ABM can be used to link several crop suitability maps developed by DPIPWE or other organisation.
- Crop GIS-ABM can be used for the purpose of education (especially in urban and regional planning) by helping design and planning students understand the underestimated complexity of human- natural system interaction in the planning system. Crop GIS-ABM as a 'virtual laboratory' provides an opportunity for design and planning students to change parameters and experience how policy and human decisions may influence and interact to affect land use change in the future. It presents a way for universities and students to investigate the complexity of individual decisions and behaviour in a regional and agricultural land use planning context.

To conclude

This research demonstrates the potential effectiveness of a spatial ABM as a decision support simulation tool for agricultural land use planning. The Crop GIS-ABM makes an important contribution to the body of knowledge around spatial agent-based modelling in that it was designed from the bottom-up based on the stakeholders' insights and integrates both qualitative and quantitative data in Agent Analyst software.

Agricultural land use planning research is an interdisciplinary study with dynamic processes. It is at the cross-section of philosophy (law, human judgment), sociology (human behaviours), economics (production and distribution of goods and services) and geography (human-natural system relationship, GIS). It is difficult to develop a ‘theory’ that applies in all situations. The simulation, and especially the spatial ABM, can assist to combine these disciplines to look at land use issues from different perspectives and explore the potential impacts of change. For example, this study has shown that the Crop GIS-ABM algorithms afford an opportunity to integrate biophysical conditions (geography), economic factors (gross margin) and social factors (neighbours’ proximity effects) to simulate farmers’ behaviours under different agricultural policies for better understanding of the future possible impacts of human decisions on agricultural land and water resources.

The multistage design of this research using the geodesign framework shows great promise for exploring interdisciplinary research questions that cut across the regional planning, economic and social sciences. This research has illustrated its applicability to agricultural land use planning and land use change. This study is original also in that Crop GIS-ABM was created as a simulation tool based on a farmers’ decision model (merged interpretation of interview and survey data) and it has been able to accommodate scenario analysis at both macro- and micro-scale.

The research acts to stimulate awareness of the need for better tools for agricultural land use planning and linking agricultural land use decisions to the broader scope of land use planning. Crop GIS-ABM takes planning a little closer to better capturing the cumulative impact of many individual farmer decisions. It addresses that gap. The Crop GIS-ABM model can simulate a range of land use scenarios. Real-world testing of policy impacts around land use change and agriculture is costly and sometimes impractical. Therefore the Crop GIS-ABM offers a way forward.

As a final comment, the issue of simulation accuracy and validity are inherent in researching the complex human-natural system. The dilemma around how accurate the simulation model can predict the future statement, and which method should be used in real-world, never go away in land use planning. However, there are techniques and approaches such as using triangulation of the result of the models with a modified Delphi or stakeholder expert group feedback that can be used to estimate better the accuracy and validity of the simulation outcomes. There are many unanswered questions and recommendations for further research on agricultural land use planning. This study and its positive results is just the starting point for solving complex agricultural problems using simulation tools and further development of spatial ABM.

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Appendix 1: Ethics approval

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HUMAN RESEARCH ETHICS COMMITTEE (TASMANIA) NETWORK

UTAS

25 February 2016

Professor Janelle Allison
Pro Vice-Chancellor (Community Partnerships and Regional Development)
University of Tasmania

Student Researcher: Sahar Shahpari

Sent via email

Dear Professor Allison

Re: MINIMAL RISK ETHICS APPLICATION APPROVAL
Ethics Ref: **H0015467 - Turning water into value: advanced regional modelling approaches to aid decision making**

We are pleased to advise that acting on a mandate from the Tasmania Social Sciences HREC, the Chair of the committee considered and approved the above project on 10 February 2016.

This approval constitutes ethical clearance by the Tasmania Social Sciences Human Research Ethics Committee. The decision and authority to commence the associated research may be dependent on factors beyond the remit of the ethics review process. For example, your research may need ethics clearance from other organisations or review by your research governance coordinator or Head of Department. It is your responsibility to find out if the approval of other bodies or authorities is required. It is recommended that the proposed research should not commence until you have satisfied these requirements.

Please note that this approval is for four years and is conditional upon receipt of an annual Progress Report. Ethics approval for this project will lapse if a Progress Report is not submitted.

The following conditions apply to this approval. Failure to abide by these conditions may result in suspension or discontinuation of approval.

1. It is the responsibility of the Chief Investigator to ensure that all investigators are aware of the terms of approval, to ensure the project is conducted as approved by the Ethics Committee, and to notify the Committee if any investigators are added to, or cease involvement with, the project.

A PARTNERSHIP PROGRAM IN CONJUNCTION WITH THE DEPARTMENT OF HEALTH AND HUMAN SERVICES

2. Complaints: If any complaints are received or ethical issues arise during the course of the project, investigators should advise the Executive Officer of the Ethics Committee on 03 6226 7479 or human.ethics@utas.edu.au.

3. Incidents or adverse effects: Investigators should notify the Ethics Committee immediately of any serious or unexpected adverse effects on participants or unforeseen events affecting the ethical acceptability of the project.

4. Amendments to Project: Modifications to the project must not proceed until approval is obtained from the Ethics Committee. Please submit an Amendment Form (available on our website) to notify the Ethics Committee of the proposed modifications.

5. Annual Report: Continued approval for this project is dependent on the submission of a Progress Report by the anniversary date of your approval. You will be sent a courtesy reminder closer to this date. **Failure to submit a Progress Report will mean that ethics approval for this project will lapse.**

6. Final Report: A Final Report and a copy of any published material arising from the project, either in full or abstract, must be provided at the end of the project.

Yours sincerely

Katherine Shaw
Executive Officer
Tasmania Social Sciences HREC

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Appendix 2: Interview questions <u>(H0015467)</u>

<u>Tasmanian Irrigation</u>

Code Roll Number of the Respondent ______________________________

Date of interview (dd/mm/yyyy): ______________________________

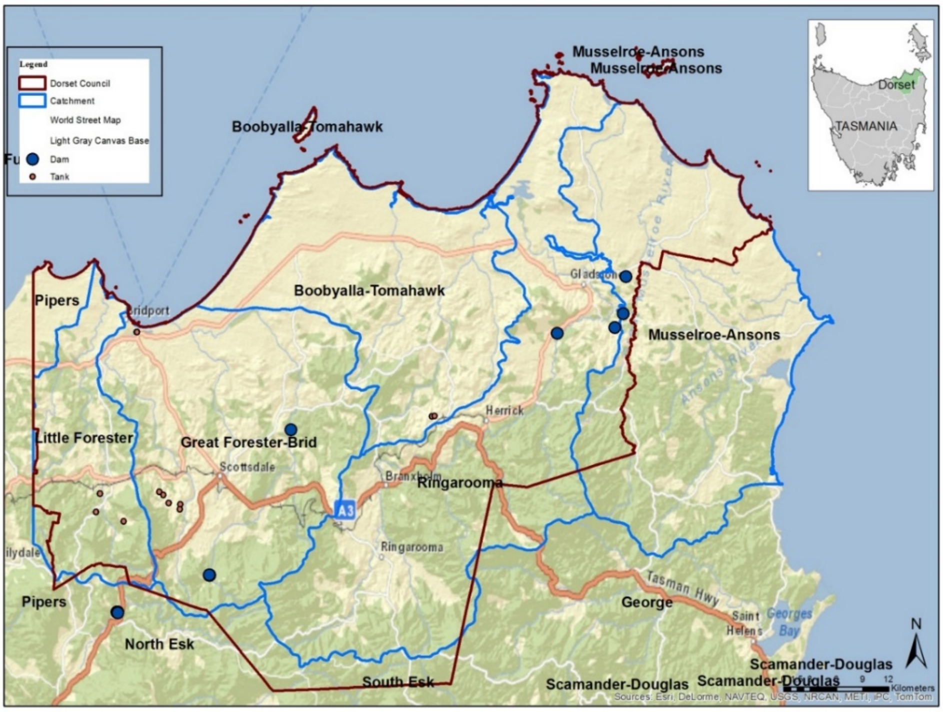
Time of starting the interview: ______________________________

Name of the Investigator (Code Roll No.): ______________________________

Optional Information

Contact Person: …………………………………………………… *Phone:* ……………………………

1. What do you think about the future of agriculture in Dorset Region?
2. What kind of irrigation infrastructure is currently available in Dorset Region?
3. Is there any plan or proposed scheme in next 5 years or in next 10 years for the region?
4. What are the critical issues for deciding to go ahead with an investment?
5. What do you think influences farmers interest in water investment in Dorset region?
6. Which part of the Dorset region are farmers more interested in investment? Please mark areas on the map



7. Why are these part/parts of Dorset region of more interest in investment?
8. What are the alternative crops/Livestock/ livestock for the Dorset region that can add value to Dorset region through guaranteed water?
9. What alternative crops/Livestock could attract farmer investment?
10. What role would the availability of processing plants have on water investment options for the Dorset region? Where would they be ideally located and why?

Agricultural services

Code Roll Number of the Respondent ________________________________

Date of interview (dd/mm/yyyy): ____

Time of starting the interview: ____

Name of the Investigator (Code Roll No.): _________________________________

Optional Information

Contact Person: .... Phone: ....

1. What do you think about the future of agriculture in Dorset Region?
2. What combination off crops/Livestock can add value to Dorset region in the future?
3. What kind of processing plant could be suitable for the region? Where? Why
4. What alternative crops/Livestock could attract processing plant investment?
5. What alternative crops/Livestock could attract farmer investment through water availability?

NRM

Code Roll Number of the Respondent ________________________________

Date of interview (dd/mm/yyyy): ____

Time of starting the interview: ____

Name of the Investigator (Code Roll No.): _________________________________

Optional Information

Contact Person: .... Phone: ....

1. What do you think about the future of agriculture in Dorset Region?
2. Are there current environmental or resource issues in the area?
3. What are the current economic issues in the area?
4. What major changes are foreseen for the region? Are they related to growth or decline?

5. Are the pressures for change being driven from inside or the outside of the area?
6. Are the anticipated changes seen as beneficial or harmful? To whom?
7. What combination off crops/Livestock can add value to Dorset region in the future?
8. What kind of processing plant could be beneficial for the region? Where? Why
9. Which impact of the possible processing plant is most important?
10. Which issues around alternative crops/Livestock for the Dorset region must be assessed by law and regulation?
11. Is there any plan and scheme for this area?
12. Are there any maps of proposed plan or past plans?

Farmers

Code Roll Number of the Respondent ________________________________

Date of interview (dd/mm/yyyy): ____

Time of starting the interview: ____

Name of the Investigator (Code Roll No.): __________________________________

Optional Information

Contact Person: …………………………………………………………………………… Phone: ……………………………………

1. What do you think about the future of agriculture in Dorset Region?
2. What are the high value crops for Dorset region? and why?
3. What are possible alternative crops/Livestock for the Dorset region in your point of view?
4. What combination off crops/Livestock can add value to Dorset region in the future? and why?
5. What kind of processing factory could be beneficial for the area? Where? And why?
6. Is the expansion of irrigation in the region seen as beneficial? To whom?
7. Are you interested in investment in buying water access?
8. Does the price of irrigation water or investment infrastructure concern you?

Dorset Council

Code Roll Number of the Respondent ________________________________

Date of interview (dd/mm/yyyy): ____

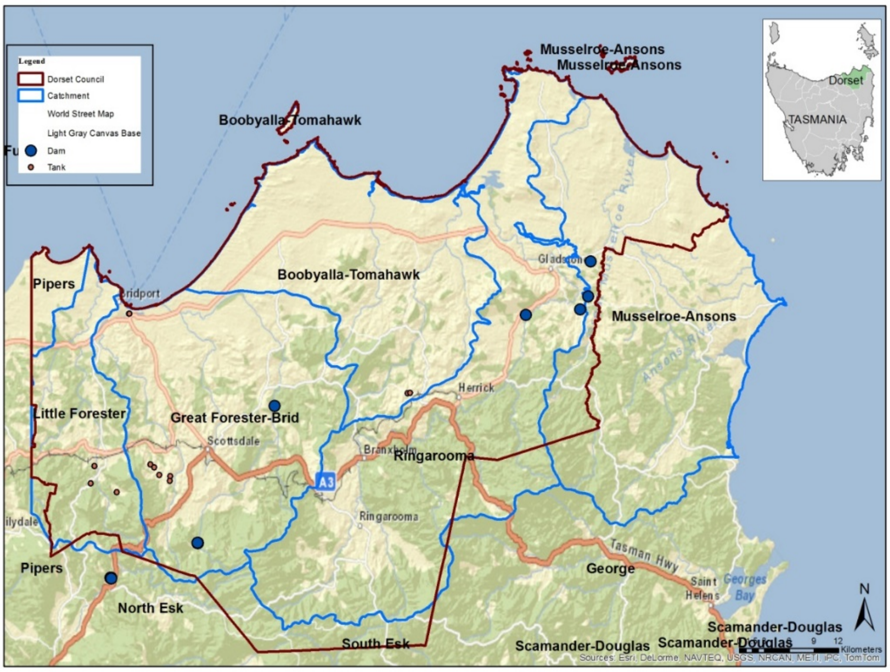
Time of starting the interview: ____

Name of the Investigator (Code Roll No.): __________________________________

Optional Information

Contact Person: …………………………………………………………………………….. Phone: ……………………………………

1. What do you think about the future of agriculture in Dorset Region?
2. What are Dorset's region physical, ecological, economic and social characteristics?
3. Is Dorset region developing or declining? In what way?
4. What major changes are foreseen for the region? Are they related to growth or decline?
5. Are the pressures for change being driven from inside or the outside of the area?
6. Is the expansion of irrigation in the region seen as beneficial? To whom?
7. Are farmers interested in investment in water availability?
8. What alternative patterns of crops could add value to Dorset region in the future?
9. What alternative crops/Livestock could attract farmer investment through water availability?
10. What kind of processing plant may be beneficial for the region? Where? Why?
11. Is there any plan and scheme for this region?
12. Are there any maps of proposed plan or past plans? What are the timeframes for these plans?
13. Which part of the Dorset regions do you think farmers would be more interested in investment in water availability? Please mark on the map



Appendix 3: Survey questionnaire

UTAS

Questionnaire: Turning water into value: advanced regional modelling approach to aid decision making (H0015467)

Code Roll Number of the Respondent :_________ Age:_________

Farmers	Processors	Irrigation Tasmania	TIA	Dorset council	NRM	Other
☐	☐	☐	☐	☐	☐	☐

The study will gather information from farmers, processors, government and non-government agencies. Personal informationgathered will be kept confidential and all comments and data will be anonymised. Your contribution is very important to this work.

Thank you for agreeing to participate

Q1. For how long have you been living/working in Dorset region?___________ *(years)*

Q2. Are you a farmer?

1. Yes
2. No please move to page (3) and complete questions (Q9, Q10, Q11, Q12,Q13)

Q3. What kind of farmer do you describe yourself? Please provide a tick one or more boxes.

Owner farmer	Cultivator farmer	Tenant farmer	Share cropper	Owner and labour farmer	Owner and tenant farmer	Other

Q4. Mainly which crops/ livestock do you grow or produce? How many times do you cultivate it?

a. First crop/ livestock _________________ __________

b. Second crop/ livestock _________________ __________

c. Third crop/ livestock _________________ __________

Q5. Which of the following means of irrigation are present in your area? Please provide a tick

Canal	Own pump	Pond	River	Water tank	Dam	Other

Page **1** of **6**

Q6. Overall are you satisfied or dissatisfied with the work done for irrigation in your area?

1. Fully satisfied
2. Somewhat satisfied
3. Somewhat dissatisfied
4. Fully dissatisfied
5. NA.

Q7. To what extent do you agree or disagree with the following statements?

Statement	strongly agree (100%)	slightly agree (75%)	neither agree nor disagree (50%)	slightly disagree (25%)	strongly disagree (0%)	comment
I am interested in finding new uses for my crops/ livestock	☐	☐	☐	☐	☐	
I am interested in farming new crops/ livestock if there is an irrigation expansion	☐	☐	☐	☐	☐	
I am interested in farming new crops/ livestock if it is profitable	☐	☐	☐	☐	☐	
I am interested in farming new crops/ livestock if there is a market	☐	☐	☐	☐	☐	
I am interested in farming new crops/ livestockif there is a processing plant in Dorset region	☐	☐	☐	☐	☐	
I have investigated crops/ livestockfor industrial use	☐	☐	☐	☐	☐	

Q8. Farmers take suggestions from different people to gather information. Generally, from whom you take suggestions on the following issues?

Statement	Self	Friend relatives	neighbours	Agricultural expert	Government agency	Websites / social media	other
I mostly take suggestion for farming **new crops/ livestock** from?	☐	☐	☐	☐	☐	☐	☐
I mostly take suggestion for investment in **irrigation scheme** from?	☐	☐	☐	☐	☐	☐	☐
I mostly take suggestion for **fertilizer** from?	☐	☐	☐	☐	☐	☐	☐
I mostly take suggestion for finding a **market** from?	☐	☐	☐	☐	☐	☐	☐

Page **2** of **6**

Statement	Self	Friend relatives	neighbours	Agricultural expert	Government agency	Websites / social media	other
I mostly take suggestion for **farming equipment** from?	☐	☐	☐	☐	☐	☐	☐

Q9. What crops/ livestock will be most important to grow or produce in the Dorset region in the next 10 years?

Crops/ livestock		not important	neutral	important	very important
Traditional crops / livestock	Poppy	☐	☐	☐	☐
	Milk and dairy	☐	☐	☐	☐
	Livestock	☐	☐	☐	☐
	Vegetables	☐	☐	☐	☐
	Grapes	☐	☐	☐	☐
	Potato	☐	☐	☐	☐
	Onion	☐	☐	☐	☐
Alternative crops	Rhubarb	☐	☐	☐	☐
	Pasture seed	☐	☐	☐	☐
	lavender	☐	☐	☐	☐
	Chinese herb	☐	☐	☐	☐
	Strawberry	☐	☐	☐	☐
	Carrot seeds	☐	☐	☐	☐
Your Suggestion for alternative crops	1-	☐	☐	☐	☐
	2-	☐	☐	☐	☐
	3-	☐	☐	☐	☐
	4-	☐	☐	☐	☐

Q10. To what extent do you agree or disagree with the following statements?

Statement	Ranking amount of Agreement				
	strongly agree (100%)	slightly agree (75%)	neither agree nor disagree (50%)	slightly disagree (25%)	strongly disagree (0%)
Whatever the stated benefits farmers do not plan to grow alternative crops/ livestock	☐	☐	☐	☐	☐
With the right level of support, farmers will actively consider growing alternative crop	☐	☐	☐	☐	☐
Farmers would not grow alternative crops/ livestock alone but would consider joining a cooperative of growers linked to a processing plant.	☐	☐	☐	☐	☐

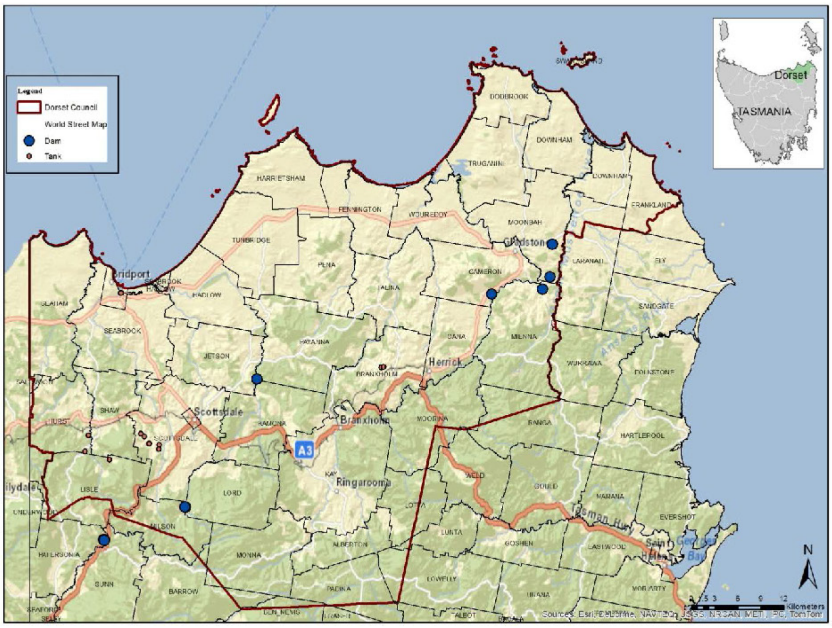
Q11. What factors will be most important in a decision for growing alternative crops/ livestock in the Dorset region?

Factors		not important	neutral	important	very important
Economic factors	Transport costs to market	☐	☐	☐	☐
	Transport costs to nearest processing plant	☐	☐	☐	☐
	Government support/subsidy	☐	☐	☐	☐
	irrigation costs	☐	☐	☐	☐
	profitability	☐	☐	☐	☐
	A forecast that demand for processing products is going to increase	☐	☐	☐	☐
Social factors	Neighbour's decision about growing alternative crops/ livestock	☐	☐	☐	☐
	Labour availability	☐	☐	☐	☐
	Experience of growing alternative crops	☐	☐	☐	☐
	Popularity of alternative crops/ livestock/ livestock among farmers	☐	☐	☐	☐
Environmental factors	The perceived environmental benefit	☐	☐	☐	☐
	Farm capacity	☐	☐	☐	☐
	The local climatic conditions	☐	☐	☐	☐

Q12. To what extent do you agree or disagree with the following statements?

Scenarios for the future of Dorset region	Ranking amount of Agreement				
	strongly agree (100%)	slightly agree (75%)	neither agree nor disagree (50%)	slightly disagree (25%)	strongly disagree (0%)
In next 10 years, if the irrigation will be expanded, Dorset region would produce just traditional crops/ livestock	☐	☐	☐	☐	☐
In next 10 years, if the irrigation will be expanded, Dorset region would partially produce alternative crops/ livestock.	☐	☐	☐	☐	☐
In next 10 years, if there will be a cooperative of growers linked to a processing plant within the area, Dorset region will produce half traditional crops/ livestock with half alternative crops/ livestock by irrigation expansion.	☐	☐	☐	☐	☐
Other Proposed scenario :					
1-					
2-					

Q13. Which part of Dorset regions are farmers more interested in new farming system or new crops/ livestock? Please mark on the map.



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THIS IS THE END OF THE QUESTIONNAIRE.

THANK YOU VERY MUCH FOR YOUR TIME AND EFFORT!

Appendix 4: Summary of qualitative findings

The table below summarises the results of qualitative analysis and describes the findings. The themes are stated based on the research questions, and the meaning describes what the theme is all about, and the evidence shows the quotes from information to support the theme.

Appendix 4 i Summary of qualitative analysis and findings

Theme	Frequency	Meaning	Evidence
Theme 1: positive futures for agriculture in the Dorset region	18	Peoples' perspective and insights about the future of agriculture in the Dorset region is positive	There's certainly a lot of potential in the region. We've got good soils. We've got a really good climate, have reasonably reliable rainfall. We're in the process of nailing down another irrigation scheme which will be the third for the district, seeing that we already had the one at.....and the one at Ringarooma. It certainly gives us security and reliability A106 I think all the work we've done in Dorset really shows that the economy of Dorset is going to be driven by its natural resources. It's natural resources are primarily agriculture, forestry, and, I guess, an emerging tourism industry. Agriculture is going to remain a really big part of the economy of Dorset. A109

Theme 2: The characteristics of the farmland	19	One of the critical considerations for investing in the irrigation scheme is the land capability and crop suitability of the farmland	in terms of land capability limits on the sort of crops you can grow, once you get beyond that red soil area. A106
Theme 3: The profitability and market price of alternative crops/livestock as a decision factor	15	The market determines prices for selling crops and costs associated with growing crops affect farmers' decision to invest in irrigation and alternative crops/livestock	that's probably borderline economic benefit.A103 There's only one thing that will influence the farmer. They want to put water to make money. It's that simple. A108 The drivers of change on farms, whether it be to adopt irrigation, or whether it's to have a new type of crop, or a new pasture animal system, or something, that's driven by dollars, by personality. A110
Theme 4: Irrigation availability as a decision factor	16	Access to irrigation determines the tendency to choose alternative crops/livestock	"… here had quite sand, not basalt soil, it's quite sandy soils but they are very large open plains and very easy for irrigation so you can put big pivot irrigators, so they've already been cleared, and it's basically ready for farming. Probably with irrigation and with suitable fertilisers, could be quite a productive area. A120
Theme 5: Neighbour's decision as a decision factor for investing in irrigation, alternative crops/livestock	7	Neighbours fields determine the social network for investing in irrigation as well as growing new alternative crops/livestock	Huge impact, nearly all the farmers... In most areas, there are key successful farmers, and they watch to see what they're doing... They may not even be leaders but they might be someone who's been quite successful, and someone who's been willing to try something new and they've succeeded. They tend to watch what they're doing and then follow it. A103

Theme 6: The availability of three-phase power as a decision factor	11	The access to three-phase electricity determines the feasibility of using irrigation and affects farmers' decision to invest in irrigation schemes	It would be better if they could get 3-phase power, yes. I don't think the whole thing hinges on that. It can still be successful and go ahead without that power, I think. It would be good if we had the power there, no doubt. A111 I think there's a lot of possibility for dairy conversion through that area, through the low Forester and the Waterhouse area, but without three-phase, dairies are basically very expensive.A109
Theme 7: The accessibility of value-add processing plant is a decision factor	Milk product processing 9 Vegetable processing 5 MATS 2 Winery 1 Hemp processing 1	The insights of participants about the availability and feasibility of value-add processing plants in the Dorset region affect farmers' decision on irrigation investment and alternative crops/livestock	I think that there's certainly potential for Tasmania with those frozen products again… Potentially there might be if there are some more facilities to process the helping into a fibre A114 Vegetable processing ... A111 It would depend on how much dairy expanded. You would want a lot of dairy products to justify putting in say a factory that produces milk that produces long-life milk and milk powder, so maybe perhaps a yoghurt producer could be set up, these are possibilities. A122
Theme 8: Possible alternative crops/livestock (e.g. hemp) that could attract farmers' investment in irrigation	Current crops (dairy, beef, potato, poppies) 12 Hemp 7 Fruit 5 Grapes 3 Goat milk 2	The insights of participants about traditional crops and alternative crops/livestock in the Dorset region through expansion of irrigation	I don't think there are many options for that. No, I can't think of any. We grow higher value potatoes; we grow early generation seed potatoes which we send to the mainland, but we make sure that we've got enough water to grow those crops.A116 That's going to be dairy, potatoes, and maybe poppies at the moment. A104 Viticulture- ... because with our rich red soils. The wind is a problem, but I think we can overcome that by using farms that face east or north or northeast or east sloping A107 Farmers that have taken on we'll use it probably for dairy and … You're thinking of crops; we can go into milking sheep, we can go into the production of goat meat. A118

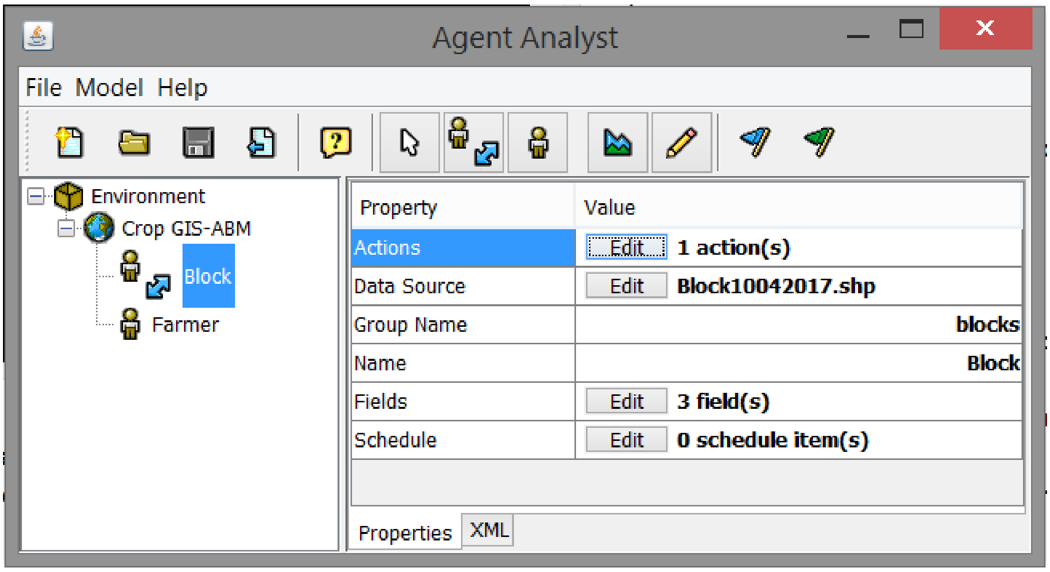
Appendix 5: ODD+D protocol

It is challenging to describe the simulation model because some aspects of the simulation model are obvious for the model developer while it is critical for them to be explained for the reader. As a result, the standard protocols needed for describing the simulation model (O'Sullivan & Perry 2013). The ODD+D protocol (Overview, Design Concepts and Details, as well as human Decision) has been recognised as a standard protocol for describing agent-based models (Polhill et al. 2008; Grimm et al. 2010; Müller et al. 2013). The ODD+D protocol was adopted for documentation of the Crop GIS-ABM model to support transparency of model description. The ODD+D protocol provides a structure for explaining the ABM by considering the human decision-making process. As the human decision-making process (stakeholders' decisions) are included in the Crop GIS-ABM model, the ODD+D protocol was a suitable protocol to structure the model documentation.

The Crop GIS-ABM model was explained in three sections namely (I) overview of the model, (II) design concept and (III) the details of initialisation and implementation. In the following sections, these three categories were explained. The software codes were deliberately not documented here because the computer codes as a live entity are constantly evolving and changing. However, the model overview, design concepts and details and the main functions (that are explained in Chapter Four and in this appendix) will not change.

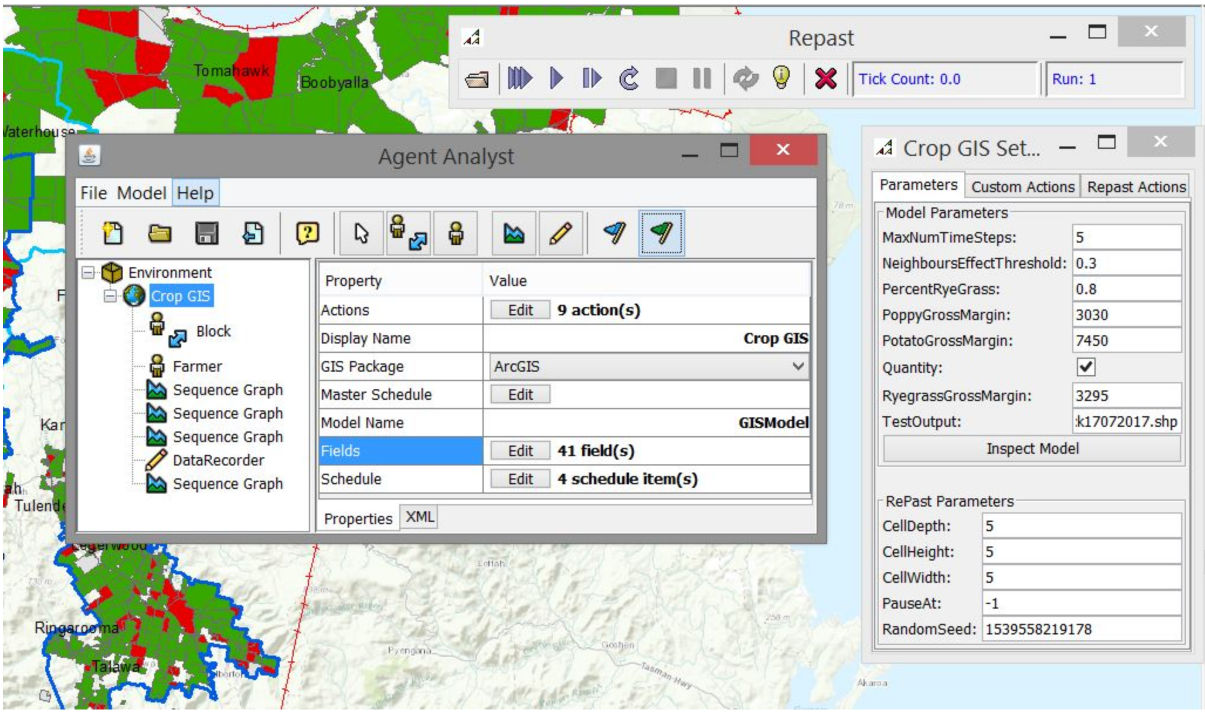
(I) <u>Overview</u>

Crop GIS-ABM model is a spatial Agent-Based Model (ABM) that was designed by the researcher and explained in Chapter Four. In the Crop GIS-ABM, a farmer as an object-oriented entity responds to changes in his/her environment autonomously through a set of rules that link information about his/her environment to his/her decision. Each land parcel as a polygon agent represents the micro-level decision model and its impacts on the region. The ABM rules based on the stakeholders' insights were developed in a GIS platform through ESRI ArcGIS Agent Analyst software to simulate the farmers' decisions on crop types in the region.



Appendix 5 I Snapshot of Components and Properties in Crop GIS-ABM in Agent Analyst software

As can be seen in the above Figure (Appendix 5 I), the left panel, called the Environment panel, displays the components of the simulation model including the Crop GIS-ABM, the vector agent called Block and the generic agent called Farmer. The Environment component at the top of the tree is responsible for the global compilation environment. The Crop GIS-ABM is a model producer component, which is concerned with initialising and master scheduling of the Block and Farmer agents. The right panel, called the Property panel, represents several properties of the components.



Appendix 5 II Snapshot of Crop GIS-ABM in ArcGIS software

The above Figure (Appendix 5 II) illustrates Crop GIS-ABM, the setting for parameters and running toolbars. The Crop GIS-ABM has four key features including two types of agents, sets of fields, sets of actions and schedules that are summarised in Chapter Four Table 5-4. The following table summarises the fields, actions and schedules that are described in detail in Chapter Five.

Appendix 5 III Summary of the fields, actions and schedules

Parameters	Field	Data type	Description
Time steps	MaxNumTimeStep	Double	The number of time steps specified for a model run
Neighbours' proximity effects threshold	NeighboursEffectsThreshold	Double	The maximum tolerable number of different neighbours who produce different crops to the agent as a fraction of all neighbours
Ryegrass percentage	PercentRyeGrass	Double	The ratio of agents that produce ryegrass to the total number of agents
Gross margin	GrossMarginPoppy GrossMarginPotato GrossMarginRyegrass GrossMarginHemp	Double	The growth margin of the ryegrass, poppy and potato were defined as parameters to allow the model used to change them. Farm gross margins calculate all annual

			production costs and income of a particular crop on a per-hectare basis
Irrigation availability	Irrigation	Boolean	The choice between having or not having a decision rule based on Irrigation area in the region
Quantity/ Area	Quantity	Boolean	The choice between a decision rule based on a count of different neighbours and a decision rule based on an area of different neighbours

Actions	Description
initAgents	Call upon the agents to boot up and call other actions to initialise the agents
updateDisplay	Update and refresh the ArcMap display
writeAgents	Set the current block attribute and save the changes to the shapefile
setupBlocks	Load spatial data and set blocks and their neighbourhood
printNeighbours	Count the number of each block's neighbours and print them to console
CropArea	Count the number and calculate the area of each crop type
step	Farmer agent performs actions at each time step based on other actions
chooseQuantity	Check crop dissimilarity within the neighbourhood based on the number of neighbours and compare the tolerance threshold
chooseArea	Check crop dissimilarity based on the area of crops produced with neighbours based on the tolerance threshold
CropRotation	Check the last year crop type for rotation, find a new crop and change the current crop
GrossMargin	Calculate the gross margin of the crops (ryegrass, poppy and hemp) and choose the most profitable crop
GrossMarginIrr	Consider the gross margin of the crop by calculating the crop's suitable area plus the marginal area in the parcel
EndTimeStepUpdate	The actions are executed at the end of each time step (year) and provide a summary report

Actions	Schedule		
	Year (1)	Year (2, 3, 4…9)	Year (10)
initAgents	*		
writeAgents	*		
setupBlocks	*		
CropArea	*	*	*
GrossMargin	*	*	*
GrossMarginIrr	*	*	*
step	*	*	*
chooseQuantity	*	*	*
chooseArea	*	*	*
printNeighbours	*	*	*

updateDisplay	*								*								*				
writeAgents		*								*								*			
step			*								*								*		
CropRotation				*								*								*	
EndTimeStepUpdate																					*

In Crop GIS-ABM, the regional land-use pattern emerges as a result of the interactions between farmers and their land parcels under parameters at the farm level. It is notable that the crop patterns in the region emerge from farmers' decisions at the farm scale. Further, the distribution pattern of crops and farming practice is the result of multiple parameters (e.g. neighbour's farm, gross margin, and irrigation expansion). The pattern shows spatially which part of the region produces alternative and heterogeneous crops instead of the homogenous dominance of crops.

(II) Design concept

In the following section, the overall design concept of the Crop GIS-ABM model was described based on the ODD+D protocol. The decision concept included some sub-sections on (II.i) Background, (II.ii) Decision making process, (II.iii) Learning, (II.iv) Sensing (II.v) Prediction, (II.vi) Interaction, (II.vii) Collective, (II.viii) Heterogeneity, (II.ix) Stochasticity, and (II.x) Observation of the Crop GIS-ABM model. The Crop GIS-ABM model was developed in the context of ABM and GIS.

The underlying assumptions are that each Farmer agent has a land parcel and makes a decision to overcome the biophysical constraints, and optimise the profits in regard to the land parcel. The agent gets the information about three options of crops (traditional or new alternative crops/livestock), compares the suitable areas of each crop and calculates the gross margin of each crop based on their land capability. The agent then looks at irrigation availability and at the neighbours' crop type decisions. Further, the agent has a virtual memory to remember their last year crop in order to rotate it if necessary. For this model there are some key components:

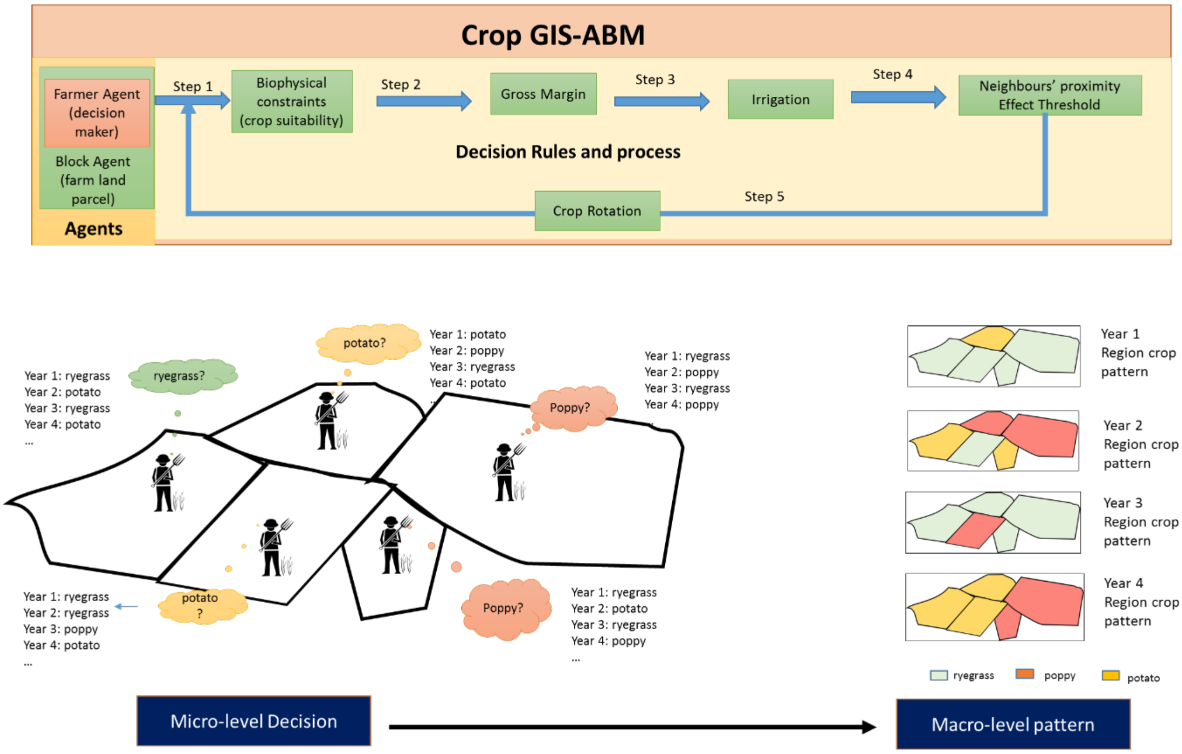
(II.i) Background:

The theoretical background of Crop GIS-ABM was described in Chapter Four. In Crop GIS-ABM, the regional land use pattern emerges as a result of the interactions between farmers and their land parcels under parameters at the farm level. It is notable that the crop patterns in the region emerge from farmers' decisions on the farm scale. The patterns show spatially which part of the region produces alternative and heterogeneous crops instead of the homogenous dominance of crops.

(II.ii) Decision-making process

Crop GIS-ABM model can simulate decision-making about land and water at the regional level as well as at individual farm level. At macro-level decision-making, the agricultural policies and strategies influence the farmers' decisions. For example, a State company can decide on the number and location of irrigation districts, or an industry body might make a decision on establishing a processing plant. By contrast at micro-level decision-making, Farmer agents are affected by macro-level decisions and execute other parameters to make a decision. In Crop GIS-ABM, Farmers try to optimise their decisions for choosing the crop each year based on the evaluation of their last crop production and the gross margin of the new crop. Social network and neighbours' crop choice play a role in their decisions. The uncertainty in farmers' decisions is implicitly included in the model, for example by taking last year crop and rotating the crop if necessary, and by taking into account the gross margin, the innovation adoption ratio and the neighbours' proximity effects of the different social networks.

The process of decision-making in the Crop GIS- ABM is illustrated in Appendix 5 Figure 3, which also describes how the Farmer agent makes decisions. In the beginning, the model-user sets the parameters. Crop GIS-ABM represents the result of farmers' decision on the parcel of land area. Each iteration of the time step simulates a year for farmers to choose strategies to change the crop of a parcel.



Appendix 5 IV Decision-making process

Further details about the decision-making process were described in Chapter Five.

(II.iii) Learning

Learning in ODD+D means whether or not agents change their decision rules over time because of their experience (Müller et al. 2013). In Crop GIS-ABM, the Farmer agent has a memory of last year crop and learns from the neighbours. The learning process is included in the model through farmers' interaction with each other. The Farmer agents may change their decisions as a consequence of their neighbour's decision.

(II.iv) Sensing

In Crop GIS-ABM, Farmer agent is assumed to access spatial information and have a sense of spatial scale from Block agents. The sensing for a Farmer agent is based on his/her own soil, suitable and marginal land for crops as well as the gross margin of the crop yield, the availability of irrigation, their social network and personal value.

(II.v) Prediction

In Crop GIS-ABM, Farmer agent is assumed to act on the value of variables and different parameters at the farm scale. The spatial pattern of land use change emerges during the simulation at the regional level, and the results demonstrate how the macro-level patterns are influenced by the farmer's decision at the micro-level. Farmer agent does not predict the future impact of their decisions. The emergence of crop patterns gives the opportunity to model-users to explore the impacts of agricultural scenarios and the possibility of crop adoption in the Dorset region.

(II.vi) Interaction

The interactions among Agents depend on the location of the land farm, and its relation to the neighbours and the irrigation districts. Farmer agents interact with each other and with their environment in each time step of the simulation, and they make choices to produce different types of crop (e.g. ryegrass, poppy or hemp). The farm lands (Block agents) are changed upon the farmers' decisions based on parameters such as gross margin and interaction with the neighbours' land. As a result, a region's crop pattern emerges based on the agents' interaction and the impact of farmers' decisions.

(II.vii) Collective

Collective in Crop GIS-ABM indicates whether the agents are grouped or belonged to aggregations. The Farmer agent chooses the crops/livestock for his/her land parcel in each time step. The aggregation of the crop types in the region emerges as a crop pattern, which is then illustrated as a regional crop map in the ArcGIS display. The crop pattern emerges through the simulation and shows the individual farmer's decision on crop types when the map is enlarged, as well as the aggregation of farmers' decisions that shape the regional pattern of crops.

(II.viii) Heterogeneity

The agent in Crop GIS-ABM is heterogenic because they differ in parameters. There are two classes of agents in the Crop GIS-ABM. A Block agent represents a spatial vector layer, and a Farmer agent (generic agent) represents an individual farmer who resides in the Block agent. The Farmer agent is the subject of the model who is a decision maker, and the Block agent represents the agricultural land parcel (vector agent) is the object of the model.

(II.ix) Stochasticity

At the beginning of the simulation, the crop types (e.g. poppy, hemp and ryegrass) are randomly placed on the agricultural land. There is a level of randomness for initialising the crop type to the Block agents. There is stochasticity in spatial variability of the crop type for initialisation.

(II.x) Observation

Observation explains how data are gathered from Crop GIS-ABM. The outcome of different simulations is collected at the end of each time step as shapefile layers (ArcGIS layers). Charts produced during the simulation show the number of each crop and the gross margin for each time step. The results of the simulation (maps and statistics) can be compared for sensitivity analysis. The pattern of crops in each time step of the simulation is recorded for spatial impact analysis.

(III) <u>Details</u>

This section explains how the Crop GIS-ABM has been implemented. The Crop GIS-ABM's parameters and variables, the process and design concept were explained previously.

Following the ODD+D protocol, the implantation of the Crop GIS-ABM model was described in following subsections: (III.i) Initialisation, (III.ii) Input data, and (III.iii) Sub-models.

(III.i) Initialisation

The Crop GIS model allowed the simulation to start performing when all pre-defined parameters were accepted or justified. The parameters initialisation was explained in Chapter Five. Based on the interview and survey findings, potato, poppy and ryegrass and hemp crops were chosen for simulation. The gross margin parameters for the crops (potato, poppy and ryegrass and hemp) in the crop GIS-ABM were adopted from DPIPWE reports (Macquarie Franklin 2012, 2018a, 2018b). The Neighbours' proximity effect threshold parameter was initialised based on the literature (Ellen & Turner 1997; Sutherland et al. 2012; Vroege 2017) and survey findings. The Quantity parameter was initialised as 'True'. The Irrigation parameter was not initialised as it was assumed that irrigation would not expand during the simulation. The other pre-defined parameters were initialised as summarised in Chapter Five and summarised in Table 5-15.

(III.ii) Input data

The input data included maps (GIS layer), survey data (stakeholders' preference for top three crops/livestock), numerical data (census data, crop's gross margin). The GIS layer (shapefile[6]) was used in this study has different attributes, extracted from various GIS layers and census information. Further, it includes the biophysical information about the Dorset region such as crop suitability information, soil maps, slope maps, land capability maps, and land use maps. These spatial data were developed by DPIPWE. The irrigation expansion districts are also GIS layers.

[6] GIS shapefile is a vector layer that stores data and attribute of geographic feature in the ArcGIS ESRI software.

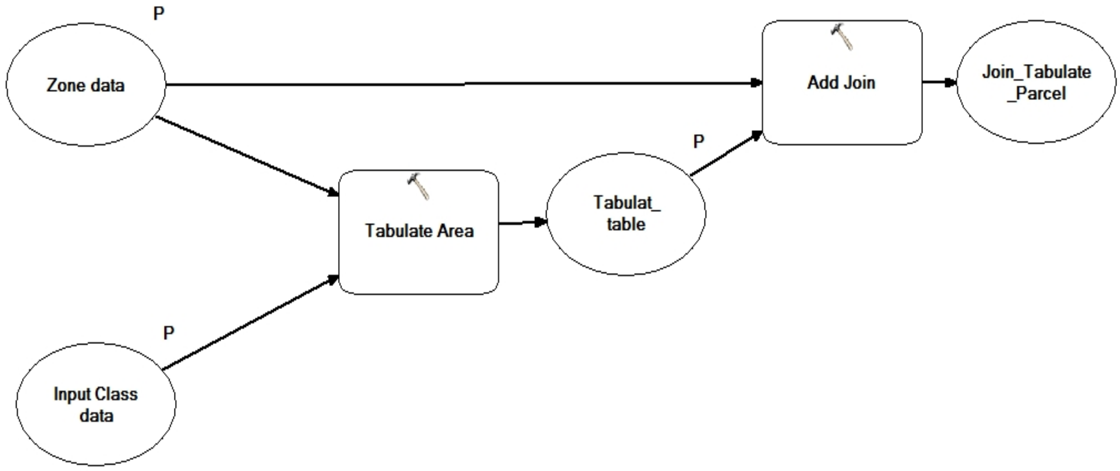
As outlined the interview and survey data were analysed, and some predefined parameter's values extracted based on the participants' insights. This information was used to define some rules and parameters in algorithms, such as the neighbours' proximity effect.

In the case of numerical data, some parameters and their predefined values were adopted from DPIPWE published information sheets for the calculation of farmers' profit crop. For example, the gross margin of crops such as hemp, ryegrass, potato and poppy were extracted from DPIPWE reports (Macquarie Franklin 2012, 2018a, 2018b).

(III.iii) Sub-models

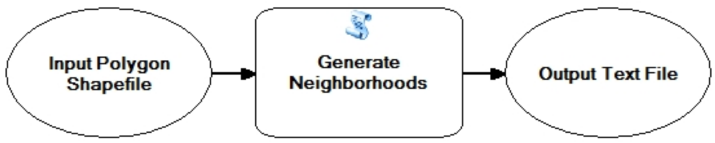
The sub-models are a separate part of the Crop GIS-ABM model. Sub-models were used for data preparation. First, the land parcel as spatial data was initialised using a Tabulate sub-model to collect the crops' suitability features. Second, the neighbourhoods and the agent neighbours were generated through a GIS/Python neighbourhood sub-model, and the information was linked to each parcel.

Tabulate sub-model: Each Block agent has a GIS layer attributes field. The spatial data (e.g. land use, land capability, crop suitability) was extracted by using a Geoprocessing model (named Tabulate sub-Model), which was excluded from the Crop GIS-ABM. The first output of the sub-model was a table that joins to the Block agent's attributes table. Figure Appendix 5 V illustrates the Tabulate sub-model and its process



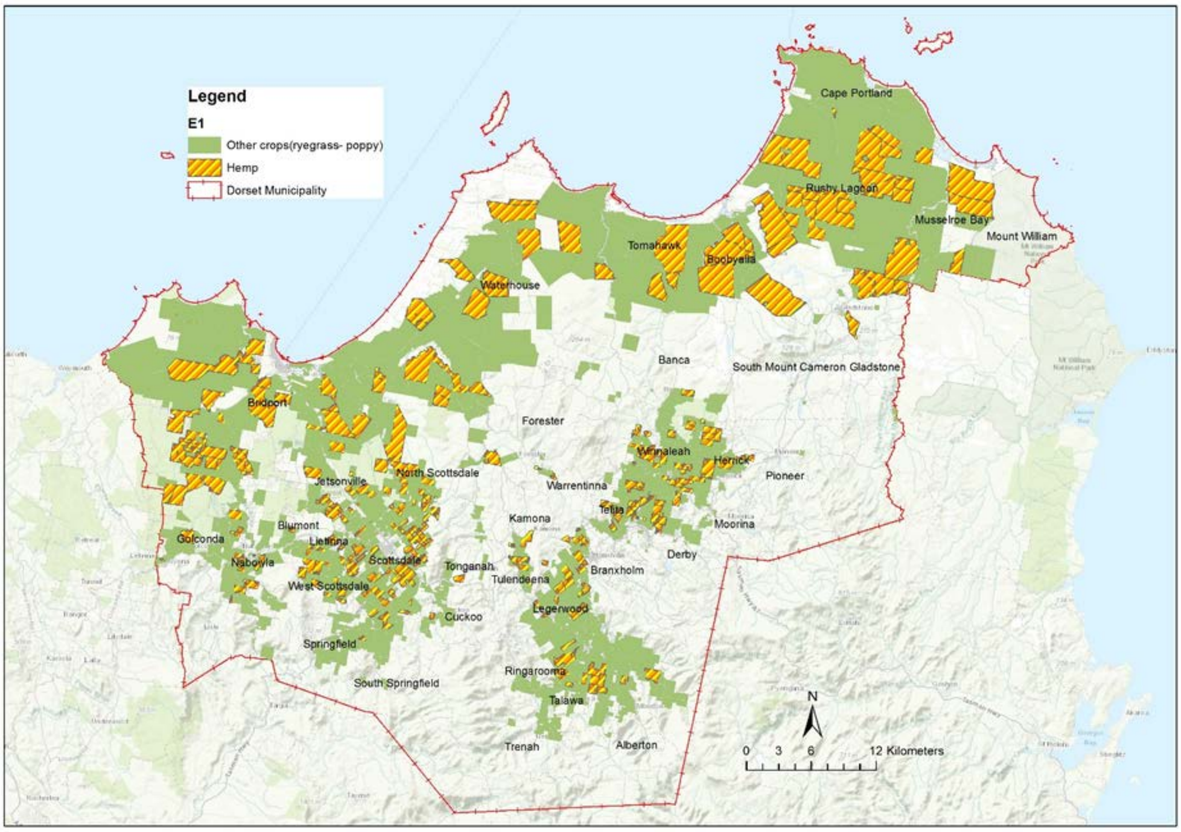
Appendix 5 V Tabulate sub-Model

GIS/Python Neighbourhood sub-model: The farmers do not have information about their neighbours. The Python Script is used to create neighbourhoods for polygon agents and farmers (Johnston 2013). The Python Script tool was adopted from Johnston (2013) to create a neighbourhood for farmers based on the location of Block agent (polygon), shared boundaries and edges of the polygons. As Appendix 5 VI shows the Block agents (Polygon Shapefile) was used as an input to the GIS/Python Neighbourhood sub-model for generating the farmers' neighbourhood file. The output of the sub-model was used as an input in the Crop GIS-ABM model.

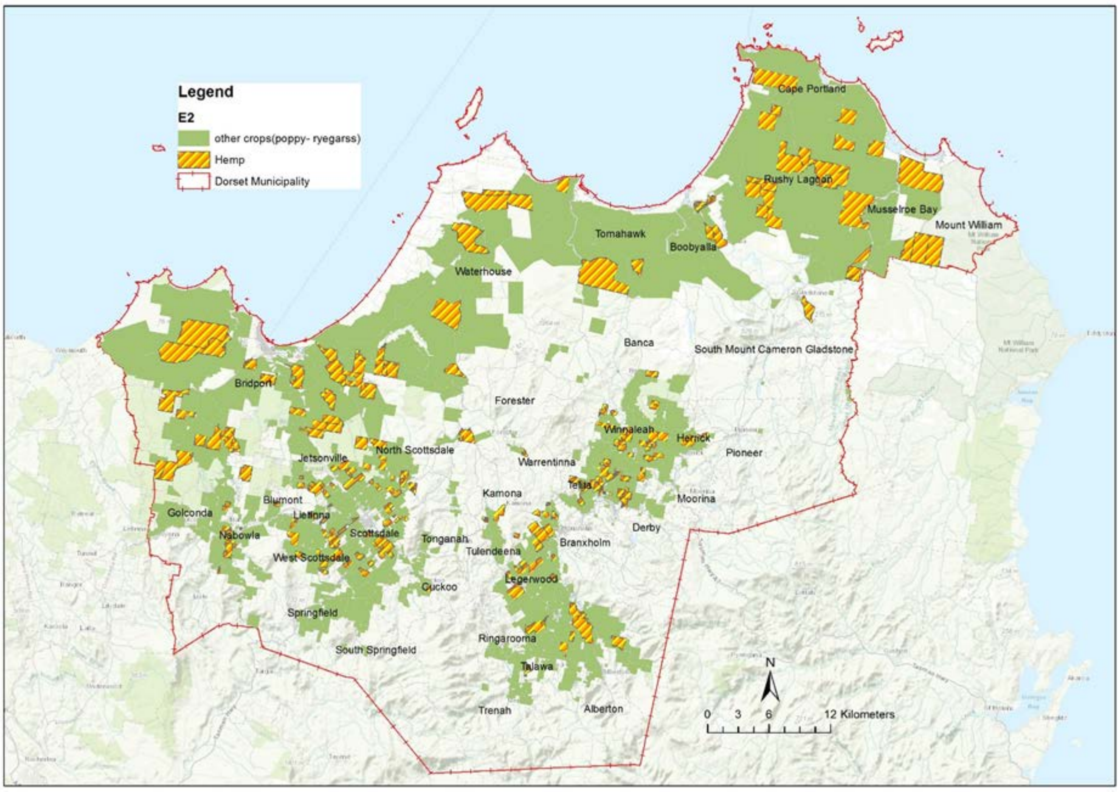


Appendix 5 VI GIS/Python Neighbourhood sub-model

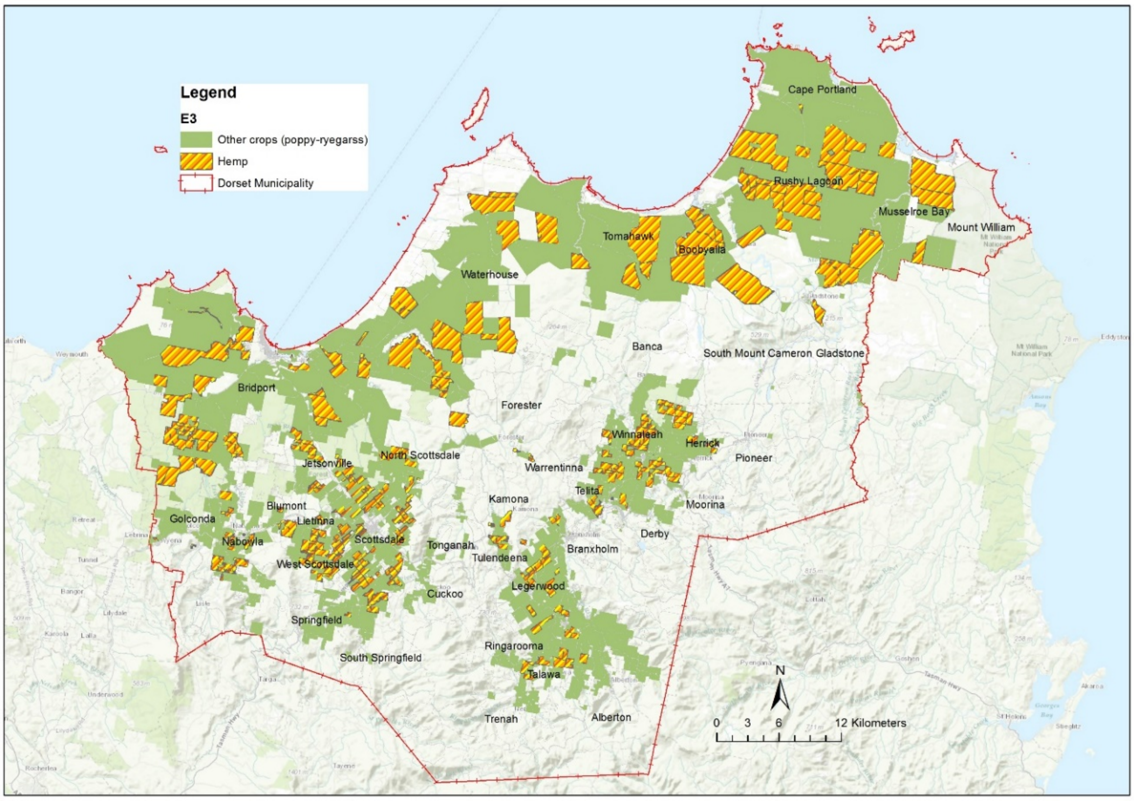
Appendix 6: Spatial diffusions of hemp under four experimental conditions,



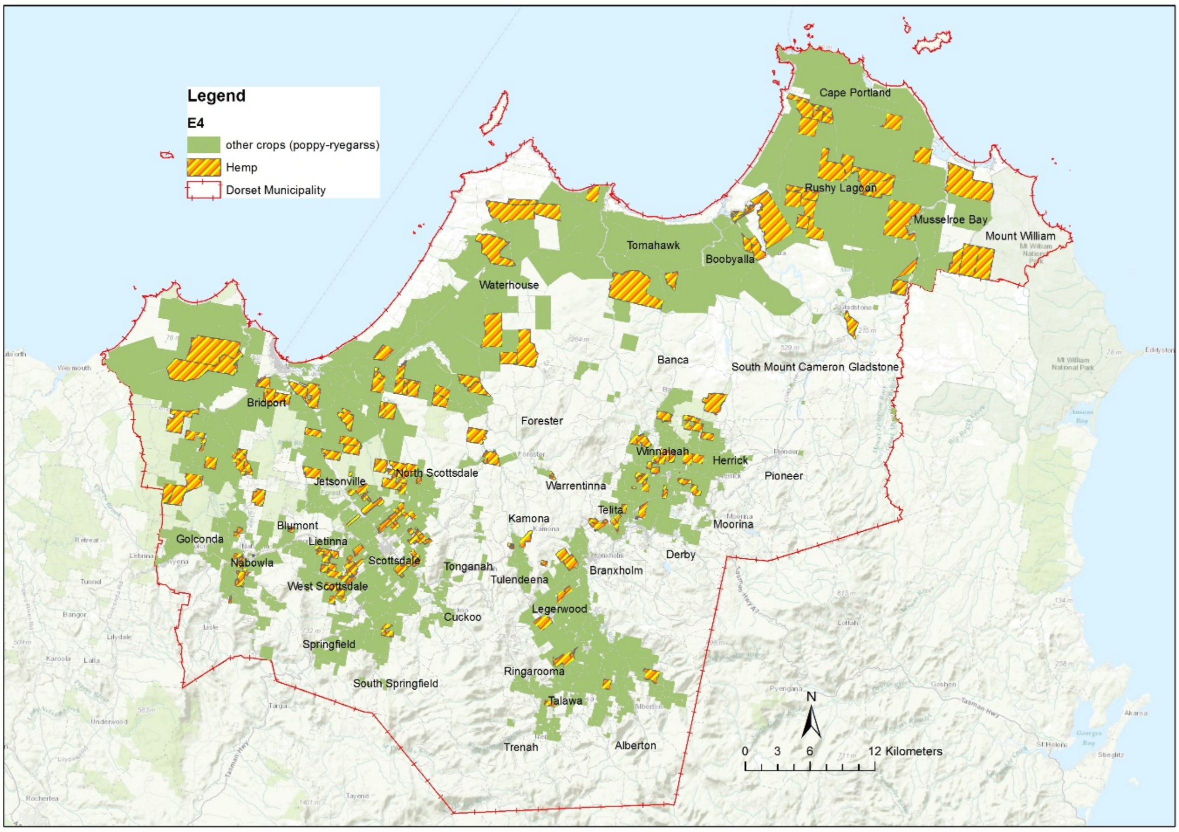
E1) low milk price without irrigation,



E2) high milk price without irrigation



E3) low milk price with irrigation



E4) high milk price with irrigation

Appendix 7: Key concepts and terminology

Some concepts and terminology were adopted to describe the focus of this research as follows:

Land cover - is the observed biophysical cover on the Earth's surface including trees, shrubs, grasses, soils, exposed rocks and water bodies, as well as anthropogenic elements such as plantations, crops and built environments (Australian Bureau of Agricultural Resource Economics Sciences 2011).

Land Use - refers to how humans use land cover (e.g. residential, industrial, commercial, agricultural, forestry, recreational) (Australian Bureau of Agricultural Resource Economics Sciences 2011). Land use data reveals information about the use of land resources including the production of goods and services such as crops, manufactures, biodiversity and natural resources protection, etc.

Geographic Information system (GIS) - is an important 'method' in quantitative geography and provides an analysis environment for spatial layers in a common coordinate system. As Murray (2010, p. 145) describes, 'a GIS is a collection of hardware, software, and associated procedures to support spatial data acquisition, management, manipulation, analysis, and display'. According to Overmann (2010), GIS is also the most significant method in regional science, and it is essential for quantifying a range of spatial facts

Agent-Based Modelling (ABM) - is a computational simulation modelling approach that reflects the actions and interactions of autonomous decision-making agents (entities) under a set of rules. The rules are typically based around 'if-else' statements (Bonabeau 2002; Helbing 2012; Steinitz 2012).

Socio-economic - circumstances or developments involving a combination of social and economic factors (Collins English Dictionary 2018).

Land use science - is an interdisciplinary science that adopts an integrated approach that couples natural and human systems, and attracts scientists from a range of disciplines, including economics, sociology, geography, geographic information systems (GIS) and remote sensing and demography (Zscheischler & Rogga 2015; Zvoleff et al. 2017).

Human-natural systems - are integrated systems in which the interaction of human and landscapes are complex and non-linear. It is also known as Coupled human and natural systems, or CHANS (Werner & McNamara 2007; Carter et al. 2014) or coupled social-ecological systems (Walker et al. 2004).

Conceptual model - is a set of concepts that represents the relationships and processes among system components, and facilitates communication and collaboration among different stakeholders, model developers and other scientists. Robinson (2008) defines a conceptual model as ‘a non-software specific description of the computer simulation model’ that provides a basis for clarifying the process of simulation model development and use.

Land parcel - a piece or unit of land that is presumed to be owned by someone, and defined by a series of measured lines that connect to form a polygon.

Appendix 8: Acronyms and Abbreviations

ABM	Agent-Based Modelling
ACLUMP	Australian Collaborative Land Use and Management Program
ALUMC	Australian land use management classification
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DPIPWE	Department of Primary Industries, Parks, Water and Environment –Tasmania
GIS	Geographic Information Systems
ICM	Integrated catchment management
LIST	Land Information System Tasmania
LUPAA	Land Use Planning and Approval Act 1993
MCAS-S	Multi-Criteria Analysis Shell for Spatial Decision Support
NAP	National Action Plan for Salinity and Water Quality
NHT	Natural Heritage Trust
NRM	Natural Resource Management
RLUS	Regional Land Use Strategies
TI	Tasmanian Irrigation
TIA	Tasmanian Institute of Agriculture (University of Tasmania)
TPPs	Tasmanian Planning Policies